STABILITY AND GEOMORPHOLOGY OF PASS CAVALLO

AND ITS FLOOD DELTA SINCE 1856,

CENTRAL TEXAS COAST

APPROVED BY SUPERVISORY COMMITTEE:

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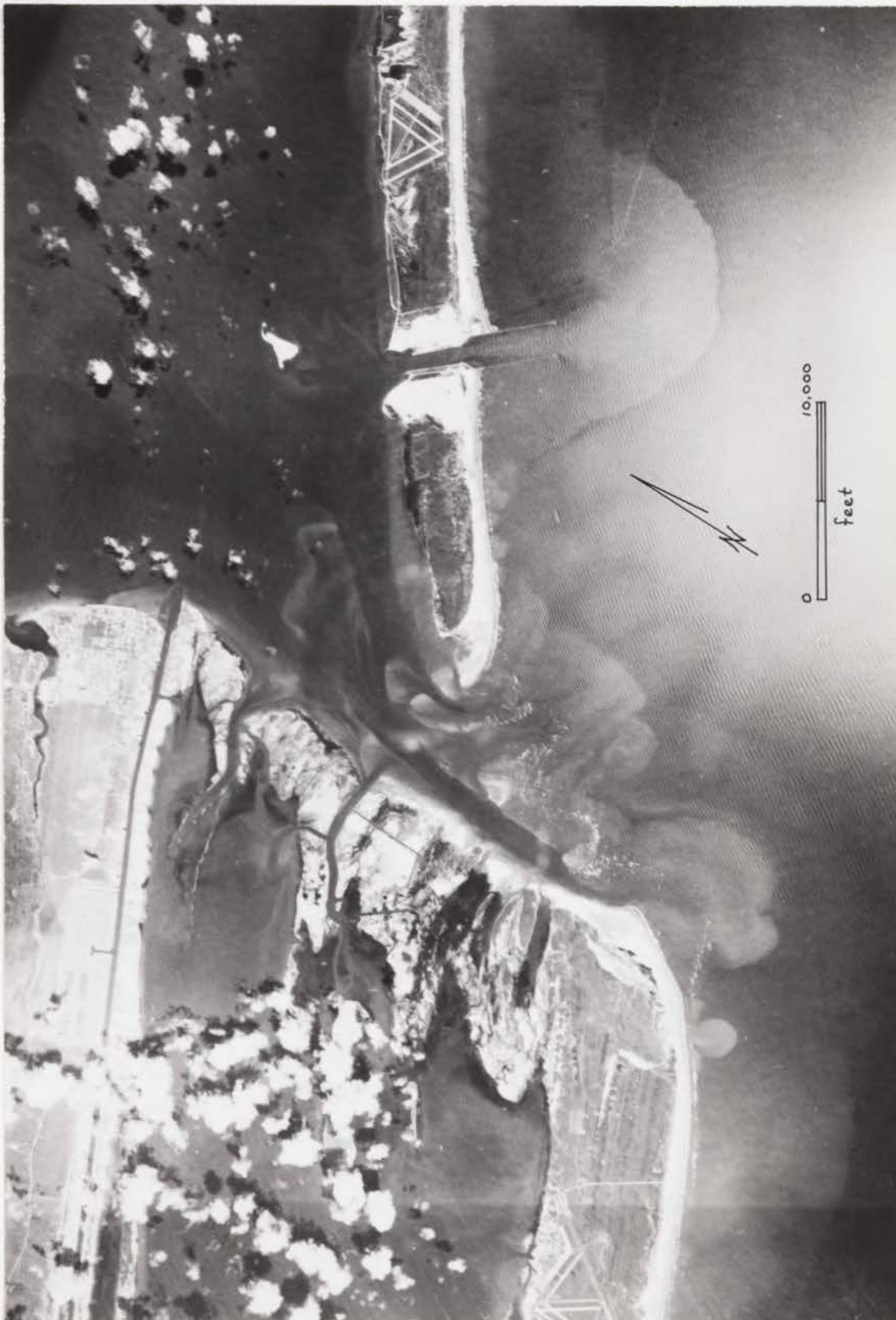
E William Behrens

FRONTISPIECE

Pass Cavallo in August 1971. Copied from a high altitude, color aerial photograph, courtesy of NASA-Johnson Space Center, Houston, Texas.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STABILITY AND GEOMORPHOLOGY OF PASS CAVALLO AND ITS FLOOD DELTA SINCE 1856, CENTRAL TEXAS COAST

by

PEGGY JEAN HARWOOD, B. A.

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF ARTS

THE UNIVERSITY OF TEXAS AT AUSTIN

May 1973

ACKNOWLEDGMENTS

When I first entered graduate school I wanted to study geomorphology. I decided to concentrate on coastal "geomorph" because I especially like the people doing coastal work--and still do.

Dr. Alan J. Scott, my supervisor, first suggested that I study the geomorphology of Texas inlets. Later one of his other graduate students Bruce H. Wilkenson, encouraged me to concentrate on Pass Cavallo, that bordered the north side of his dissertation area, Matagorda Island. This arrangement provided me with several trips to the flood delta and to the pass with Bruce and his boat (the "G.K.") to check photomapping. I learned to truly respect the power of winter storms while trying to get about in Bruce's small boat during two "blue" northers. I owe a great deal to Bruce for his optimism, stubbornness and ceaseless energy. I learned a lot from him.

Some of the ideas in this thesis have weathered many a loud, but friendly argument with Dr. J. H. McGowan in the Bureau of Economic Geology, with my student editor, Bruce Wilkenson, and with Dr. Alan J. Scott. Dr. Victor Baker also spent some time reviewing my analysis of tidal discharge and inlet geometry. To my other committee members, Dr. E. W. Behrens, Jr., at the Marine Science Institute in Port Aransas, and Dr. L. S. Land (frequently of Discovery Bay, Jamaica) I wish to express my deep thanks for taking time out of their busy schedules to critically review my thesis.

There are others, however, who over the years have maintained moral, financial and professional support for my studies without which I may never have finished. Dr. Keith Young was one of my first geology professors, and also my first and last employer within the department. Ms. Thelma Guion, Geology Librarian (now retired), established a magnificent library for research. The Geology Faculty sponsored my employment as a teaching assistant for five semesters, awarded me a summer fellowship and have supported my studies at every opportunity. My husband, Rod, equally shared all family responsibilities, and during the final stages of the thesis assumed all financial burdens as well. To all these people I am especially grateful.

Others whose help I appreciate during production of the thesis include Jack Bowen, photographer; Mayrene Hale, typist; and Scott Marden, draftsman.

This thesis was submitted to the supervisory committee in December 1972.

Peggy Harwood

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ABSTRACT

Because the volume of flow through an inlet is proportional to the tidal range and the area of the tidal basin, Texas tidal inlets have some of the largest tidal basins relative to their entrance area of any inlet. Matagorda Bay at Pass Cavallo has an area of about 200 square miles, but only a mean diurnal tidal range of about 1.1 feet.

From tide gage records the most important events modifying tidal currents in Pass Cavallo are the numerous wind tides each year that occur most frequently during the cooler months, November through May. Wind tides are most noticeable in Matagorda Bay because the astronomical tidal range is small, the fetch long (10-20 miles) and the depth only about 12 feet. Hurricanes and river floods that would raise water levels in Matagorda Bay by even 0.5 foot occur too infrequently to affect equilibrium conditions in the inlet.

Pass Cavallo has passed through three time periods since 1856: 1856-1930, 1930-1965, and post 1965.

Each time period was characterized by a different, and subsequently smaller tidal discharge, cross-sectional area and tidal channel length. The tidal discharge decreased between 1929 and 1935 when the Colorado River delta cut off part of east Matagorda Bay to reduce the tidal area of Matagorda Bay, and in 1965, the Matagorda Ship Channel was dredged across Matagorda Peninsula to reduce the volume of water passing through Pass Cavallo. Other features that changed with decreasing discharge, but remained stable during each time period, were the channel pattern, and location and shape of the Gulf bar and Pelican Island. During all three periods Pass Cavallo maintained stable cross-sectional shape, and tidal flow by-passing characteristics, except during the post 1965 when neither tidal flow by-passing nor bar by-passing were dominant.

Since 1856 Pass Cavallo has remained geographically stable relative to its width. The axial trough has migrated southwestward about 1000 feet during the past 100 years--or about 1/9th the distance between Matagorda Peninsula and Matagorda Island. Shorelines adjacent to the inlet also have tended to move southwestward, but at a faster rate than the axial trough. Along the western side of the pass, shoreline erosion is related to jetties interrupting sediment transport southward from the western shoreline of Matagorda Bay, and to storms eroding the constructional beach extending northward from Matagorda Island.

The modern flood delta at Pass Cavallo consists of a large, sandy platform, that is lobate into Espiritu Santo Bay with salt marsh, storm-tidal flats and tidal channels. The flood delta is located to the side of the channel pattern of Pass Cavallo, and appears to be active only during the high tides of hurricanes, tropical storms and "northers".

There are three informal physiographic provinces on the flood delta, each one reflecting a different sediment supply and energy regime inherent in each bay and in the Gulf. 1) The Gulf of Mexico Province has the largest and best-developed intertidal beaches, surge channels, storm-tidal flats and mounds of all three provinces. Sand is the dominant sediment. 2) Matagorda Bay Province includes large marsh islands and tidal channels with fewer large vegetated mounds. Shell is very abundant in mounds, and a storm-tidal flats contain more mud and encroaching salt marsh than in the Gulf province. 3) Espiritu Santo Bay Province is composed mostly of sandy mud or muddy sand sediment, with the exception of erosional shell beaches that face a north or south fetch of 1 to 2 miles. This is the richest area biologically, consisting mostly of salt marsh and grassflats.

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INTRODUCTION

Tidal inlets are studied by man in two time references. Within the short term, the span of a year or even 100 years, tidal inlets may form, migrate, shoal or even close. These rapid changes have been studied by coastal engineers for centuries, trying to provide reliable entrances to inland harbors for navigation. On a larger, geologic time scale, tidal inlets are only a small part of the depositional history of a coastline. On sandy barrier coasts, such as the Texas coast, these inlets are important (1) for the modifications they make when they migrate through the barrier island, (2) for shoaling the bay or lagoon near the inlet, and also (3) for the bayward accretion of the barrier island adjacent to the inlet.

I have attempted in this thesis to integrate the engineering approach that concentrates on physical processes, with the geologic approach that focuses on the results of those processes--sediment accumulation and erosion. The objectives of this thesis are (1) to describe changes in inlet shorelines, channel patterns, and inlet deposits at one Texas inlet, Pass Cavallo, since the first hydrographic surveys in 1856, and

(2) to determine some of the processes responsible for these changes and for the maintenance of these inlet features. To achieve these goals I have compared Pass Cavallo to inlets on other coasts via equations and relationships developed by Brunn and Gerritsen (1960) and Brunn (1966), and also to some other Texas inlets.

Tidal inlets respond to a variety of hydrologic, meteorologic and sedimentological conditions. Yet the similarities of inlets are quite pronounced in spite of the wide range in physical conditions on different coasts. Most inlets are located on coasts where the bed materials are sand-sized, and the openings are between sandy barrier islands or spits that separate a bay or lagoon from an ocean or sea (Brunn and Gerritsen, 1960). For these tidal inlets on sandy coasts, the entrance cross-sectional area and the volume of flow during part of the tidal period (or tidal discharge) tend to be proportional to the area of the tidal basin (bay or lagoon)--regardless of climatic regime or tidal characteristics (Brunn and Gerritsen, 1960; Brown, 1938).

On the central and northern Texas coast, the larger and historically permanent inlets exhibit remarkable geographic similarity (Price, 1952). For most of these large tidal inlets, the main channel or axial trough is oriented almost due north-south, the bayward "tidal delta" or flood delta is located on the south-west side of the main channel, and the southwest barrier island is offset Gulfward (Figure 1). Price (1952) concluded that the arrangement of these physiographic features was in response to the dominant southwest direction of littoral drift and also to strong north winds during winter storms pushing bay water southward. From north to south these large, permanent Texas inlets are Galveston Entrance (or Bolivar Roads), San Luis Pass, Pass Cavallo, Aransas Pass and Old Corpus Christi Pass (now closed (Figure 1).

Pass Cavallo was selected for study because this large tidal inlet has been charted several times during the past century and has never been jettied or regularly dredged (Figure 1). Also, complementary geologic studies were underway on Matagorda Island for a Ph.D. dissertation at The University of Texas at Austin by Bruce Wilkenson, and in Matagorda Bay by Dr. J. H. McGowen of the Bureau of Economic Geology for the Texas General Land Office.

In the mid-1800's, there were three large Texas inlets with maximum depths of 30-50 feet, and minimum depths of about 10 feet--Galveston Entrance, Aransas Pass and Pass Cavallo. Unlike the other two deep, natural

Figure 1

Index map of the Texas Gulf Coast and of Pass Cavallo.

Explanation for abbreviations

GB - Galveston Bay

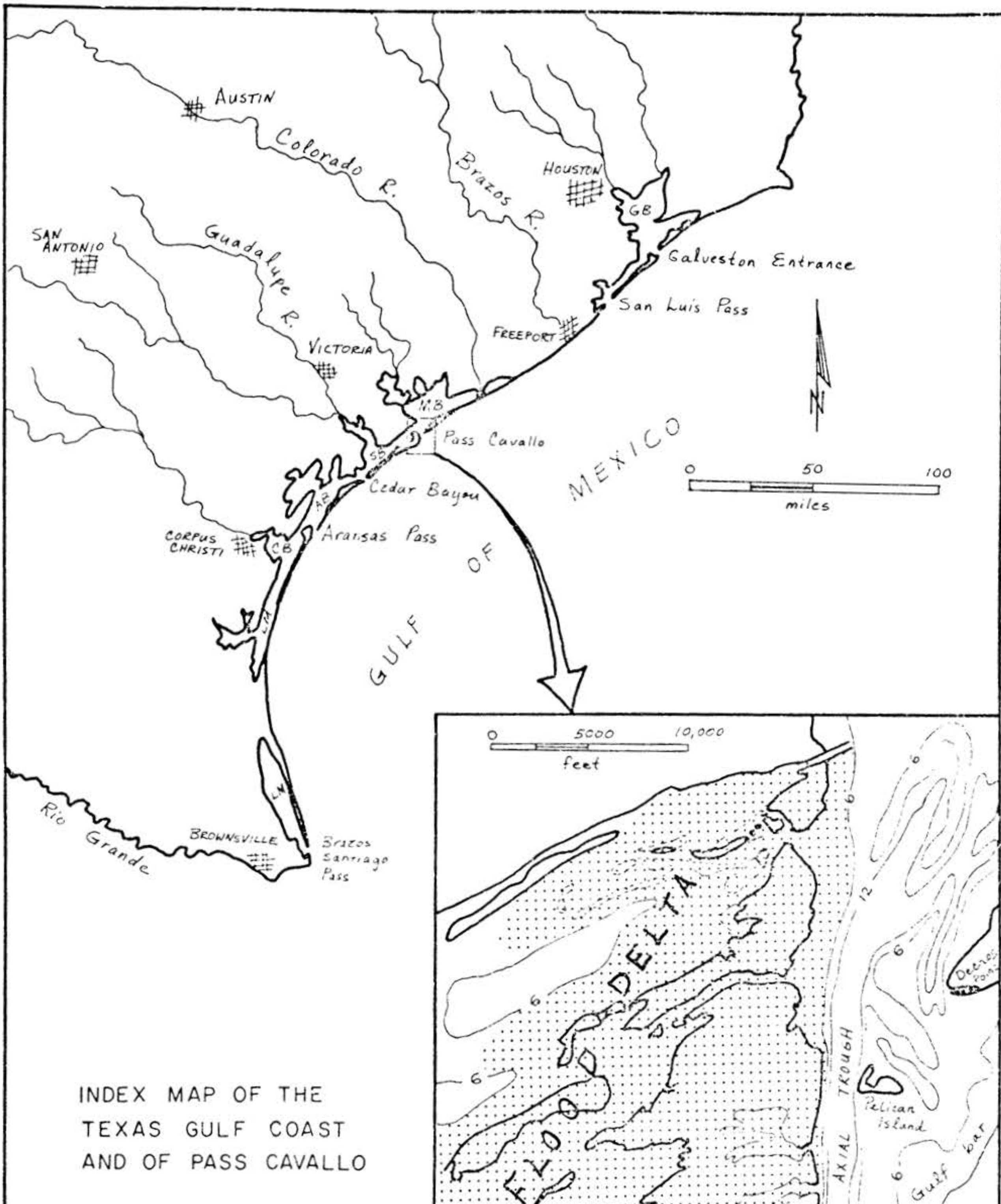
MB - Matagorda Bay

SB - San Antonio Bay

AB - Aransas Bay

CB - Corpus Christi Bay

LM - Laguna Madre



INDEX MAP OF THE
TEXAS GULF COAST
AND OF PASS CAVALLO

inlets on the coast, Pass Cavallo today is not artificially maintained in any way. This extraordinary situation was due to the early economic history of the town of Indianola on the western shoreline of Matagorda Bay.

In the mid-1800's Indianola was a strong competitor with Galveston for commercial shipping (The Dallas Morning News, 1970). Many of the German, Czech, Polish and Scandanavian immigrants to Texas landed at this seaport. The Civil War (1861-1865), followed by a period of numerous large hurricanes (1874-1886), resulted in the town being abandoned about 1887. At least two of these hurricanes destroyed about three-quarters of all buildings in Indianola (Price, 1956b). The other two successful seaports of the 1800's, Galveston and later Corpus Christi, eventually required stable entrances for deeper draft vessels so that both Galveston Entrance and Aransas Pass were jettied by the turn of the century (U.S. Coast and Geodetic Survey Charts, 520, 1905 ed.; and 210, 1913 ed.).

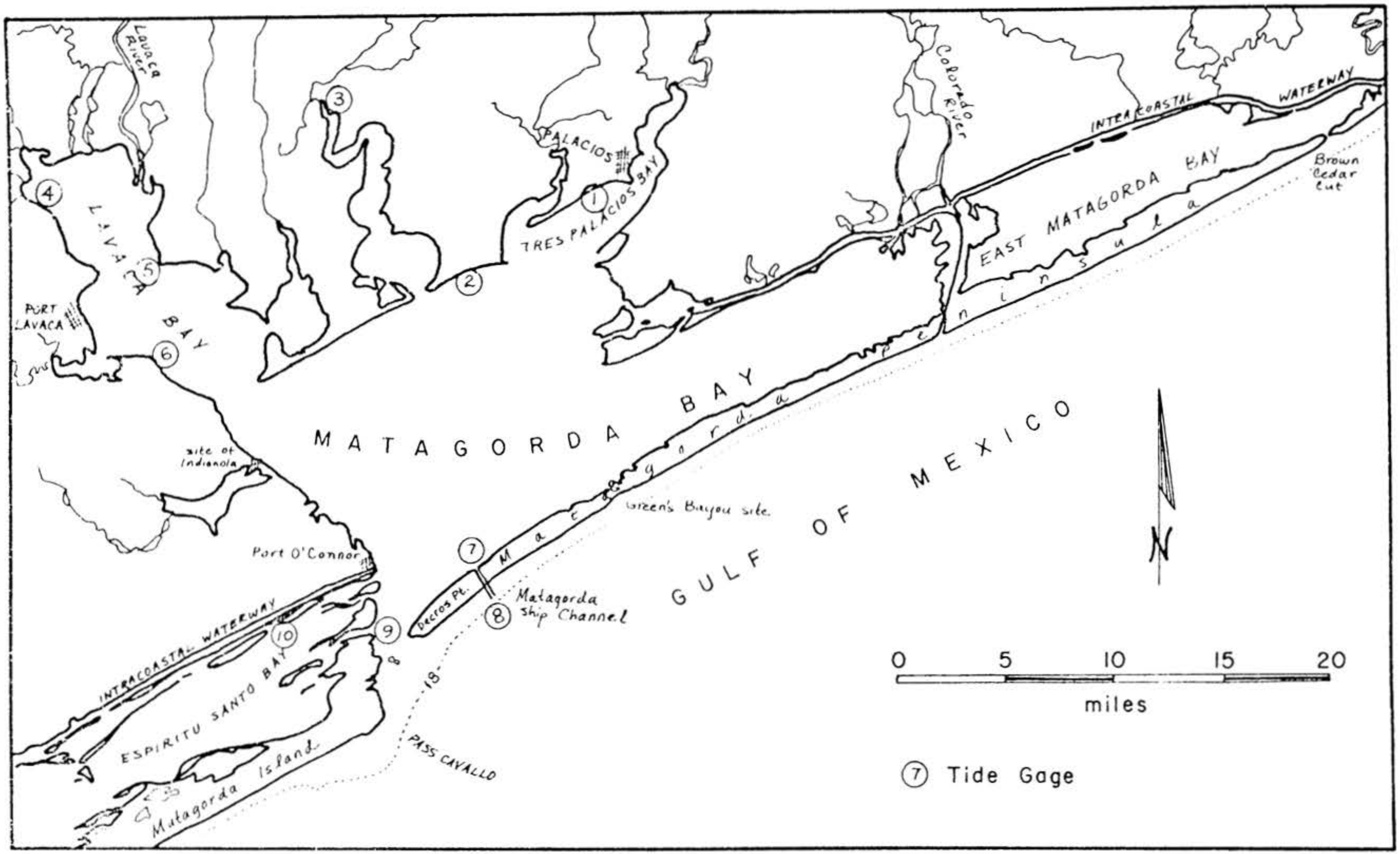
TIDES AND CURRENTS

The channel pattern of Pass Cavallo is a result of hydraulic currents that are generated by differences in water level on either side of the barrier islands. These differences in water level are produced by the astronomical tide, wind tide, hurricane tide and river flooding--either alone or in combinations.

Tide gages in the area were installed by the Corps of Engineers in 1967 and are now maintained by the U. S. Geological Survey. A copy of these tide gage records, from which the tidal behavior of Pass Cavallo and Matagorda Bay was analyzed, was borrowed from Dr. J. H. McGowen of the Bureau of Economic Geology, Austin, Texas. The location of tide gages near Pass Cavallo from 1967 to 1970 is shown in Figure 2. Continuous coverage is not available for all gages (see Appendix A) because of equipment failure. The best data are available for 1969. I concentrated on the 1969 records for the following gages: No. 9 in Saluria Bayou at Pass Cavallo, No.'s 2 and 7 in Matagorda Bay,No. 10 in Espiritu Santo Bay, and No. 8 in the Gulf of Mexico. Neither current measurements nor a contemporaneous cross-section are

Figure 2

Pass Cavallo and vicinity, Ca. 1970, showing location of tide gages. The dotted line represents the 18-foot depth contour.


Lavaca River
Colorado River
PALACIOS
TRES PALACIOS BAY
INTRACOASTAL WATERWAY
EAST MATAGORDA BAY
Brown Cedar Cut
LAVACA BAY
PORT LAVACA
MATAGORDA BAY
site of Indianola
Matagorda Peninsula
Green's Bayou site
GULF OF MEXICO
N
Port O'Connor
Decros Pt.
Matagorda Ship Channel
INTRACOASTAL WATERWAY
ESPIRITU SANTO BAY
Matagorda Island
PASS CAVALLO
18
0 5 10 15 20
miles
7 Tide Gage
1
2
3
4
5
6
7
8
9
10

available for Pass Cavallo to compare to the tidal data. Therefore, relative current strength and direction, but not velocity, were inferred from the tide curves.

Astronomical Tide

During one lunar month the Gulf tide varies from diurnal (one high and low tide each day) to semi-diurnal (two high and low tides each day) (Marmer, 1954). Diurnal tides occur when the moon is at the greatest declination north or south, and have the greatest range. Diurnal tides are more common than semidiurnal tides, which occur for two to three days twice a month when the moon is at the equator. Inside Pass Cavallo the tidal range is about 2.3 feet at moon's greatest declination (spring tides) and about 0.6 feet at zero declination (neap tides) (U. S. Coast Chart No. 208, 1918 ed.). The tidal range in the Gulf at these times would be slightly larger. Figure 3 shows a comparison of the observed tide curve at gage 8 in the Gulf at the tide curve computed from the Tide Tables (U. S. Coast and Geodetic Survey, 1969), during a period when there were no observable wind tides.

Tide Tables (U. S. Coast and Geodetic Survey, 1969) give average figures for the tidal range at Pass Cavallo that differ slightly from the Gulf tide curves

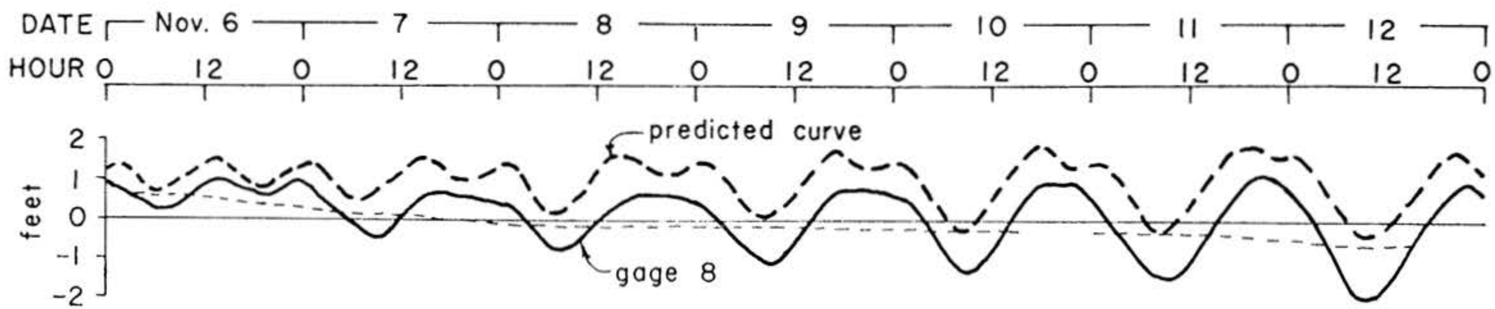


Figure 3. Comparison of observed and predicted tide curves in the Gulf of Mexico at Pass Cavallo, November 6 - 12, 1969. Both semidiurnal and diurnal tides occur. During this period, wind was from a southerly direction at speeds generally less than 10 mph, and observed mean water level (MWL) was almost 1 foot lower than predicted in the Tide Tables. Datum is mean sea level (MSL) established by the Corps of Engineers when tide gage 8 was installed.

at gage 8. The average diurnal range at gage 8 for 3 months during 1969 was about 2.0 feet. The tidal range from the Tide Tables during the same period was 1.4 feet.

This difference is consistent with figures for different tidal ranges observed in the vicinity of Galveston Entrance. At Galveston Entrance, the average diurnal tidal range in the Gulf is about 2.0 feet and inside the inlet at the city of Galveston, 1.4 feet. The figures at Pass Cavallo probably were based on a tide gage located in the inlet, most likely near Saluria Bayou (Figure 2).

The tidal range in bays and lagoons is a function of the cross-sectional area of the opening to the Gulf or with another bay, and the exciting tidal range. And as the tide moves into each successive bay or lagoon the tidal range decreases. For example, in the Gulf during February, November and June, 1969, the average diurnal tidal range was 2.0 feet. In Matagorda Bay (gages 2 and 7), which is connected with the Gulf through Pass Cavallo and the Matagorda Ship Channel, the tidal range was about 1.1 feet. During the same 3 months, Espiritu Santo Bay, a lagoon that connects through small tidal channels with Matagorda Bay on its east end and with San Antonio on its west end, had a tidal range of only 0.3 foot (gage 10).

During spring tides, the tidal range in the Gulf is about 3.0 feet, in Matagorda Bay about 1.5 feet and in Espiritu Santo Bay about 0.45 foot. For comparison, the average tidal range in Galveston Bay, the largest on the Texas coast, is about 1.1 feet (U. S. Coast and Geodetic Survey, 1969, p. 240).

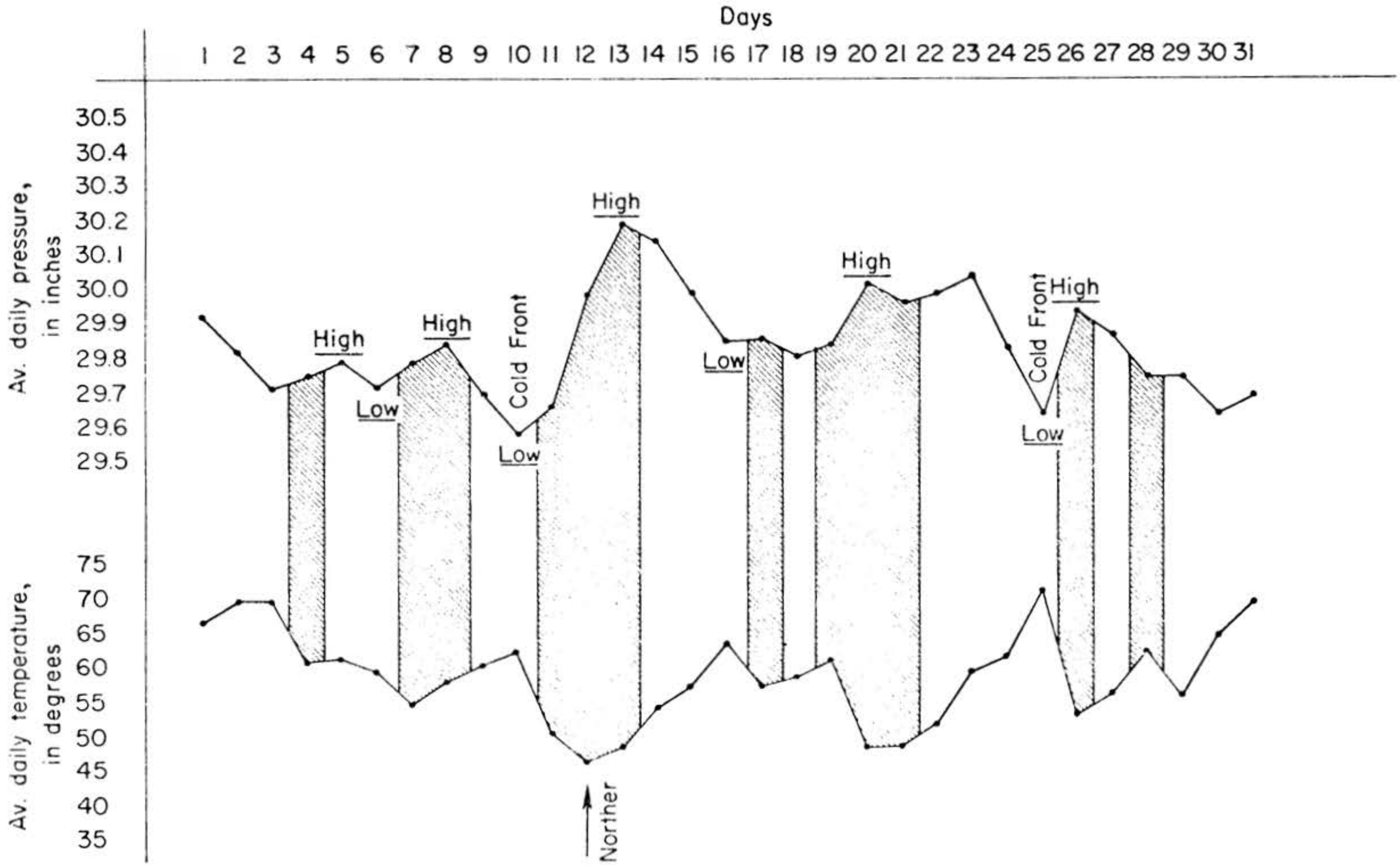
Wind Tides

Wind tides are changes in water level produced by strong winds blowing over the surface of relatively shallow water in the bays and at the Gulf shoreline. Wind tides are independent of the astronomical tides. These strong winds usually have speeds that average at least 15-20 knots and gust to 40 knots. Although they occur year round, the most spectacular wind tides occur with the passage of cyclonic (low-pressure) and anti-cyclonic (high-pressure) storms during fall, winter and spring. An example of changes in barometric pressure, temperature and wind direction with the passage of these low- and high-pressure storms is shown in Figure 4. Well-developed cold fronts are preceded by strong southerly winds and rising water level in the Gulf and in the bays. A "norther" or several days of strong northerly winds, and falling water level usually follow passage of the cold front. The period of these high and low tides

Figure 4

Changes in barometric pressure, wind direction and temperature, with the passage of high- and low-pressure storms at Victoria, Texas, March, 1970. Northerly wind directions occur between the passage of a low center and the arrival of a high center. Differences in barometric pressure and temperature are related to proximity of the storm center. The closest approach to Victoria of low and high centers occured between March 9th and 15th. Days with northerly winds are shaded.

MARCH 1970 VICTORIA, TEXAS



may be 4 or 5 days, compared to the period of 25 hours for the high and low astronomical tide.

Wind tides are important for two reasons. First, because the astronomical tide is small, wind tides disrupt the normal tidal flow through inlets. Strong southerly winds generate rising water levels in the Gulf of Mexico and may result in continuous flood currents through inlets and rising water levels in the bays. Conversely, strong northerly winds are associated with falling water levels and continuous ebb currents (Price, 1952, p. 251; Shepard and Moore, 1960, p. 123 and Fig. 6). Secondly, wind tides are important because those bay or Gulf shorelines inundated by the higher water level are also attacked by steep destructive wind waves.

Wind tides are described more accurately as meteorological tides because both barometric pressure and wind are responsible. Theoretically, increasing the atmosphere pressure by one inch of mercury will depress the water surface 13.6 inches and vice versa (Miller, 1957; Mason and Sorensen, 1971, p. 57). During 1969 at Victoria, Texas, changes in barometric pressure averaged about 0.2 inch (or about 2.7 inches of bay water level) during the periods of wind tides, with the maximum change in pressure being about 0.5 inch. During the same year, the deviation from mean bay level due to wind tides averaged about 1 foot, so that wind behavior seems to be the more important meteorological factor.

Wind tides are complex, and the magnitude of the tide is not explained by meteorological data alone. The most important non-meteorological factors are wind fetch and water depth. Saville (1953) working in Lake Okeechobee, Florida, used a simplified equation for wind setup that assumes a steady state condition in a channel of constant depth and wind blowing down the long axis of the channel. This equation shows the interrelationship between wind speed (U), fetch (x) and water depth (h) and gives the slope of the water surface as follows:

$$\frac{dS}{dx} = \frac{K\ U^2}{g(h + S)} ,$$

where S = wind setup, g = acceleration due to gravity, and K = dimensionless number that includes wind stress, bottom stress and water density. Thus the slope of the water surface (and therefore wind setup, S) will be large (relatively) if wind speed (U) is large, water depth (h) small, or fetch (x) large.

Relationships illustrated in the basic equation fit observations of wind tides on tide gage records in Espiritu Santo Bay, Matagorda Bay and the Gulf of Mexico. In general, Matagorda Bay, averaging 12 feet deep, responds with greater and more frequent wind tides than the Gulf, presumably because it is shallower. Matagorda Bay also is large and subequant (Fig. 2) with long fetch for the strongest monthly winds from N, NE, SE and S (U. S. Dept. of Commerce, 1966-1970). Espiritu Santo Bay, averaging 6 feet deep, has shortest fetch for the stronger southerly and northerly winds. Consequently wind tides in Espiritu Santo Bay are not as pronounced as those in Matagorda Bay or the Gulf, and are masked by wind tides occurring in Matagorda Bay.

The nearshore Gulf, which is about 30 feet deep 1 mile offshore and 50 feet deep about 4 miles offshore, does not always exhibit wind tides even with high speeds, especially during summer. Besides being deeper than the bays, the Gulf has only one physical boundary, allowing wind setup to disperse laterally. Consequently, noticeable wind tides occur at the Gulf shoreline with only the very strong regionally sustained winds of winter cyclonic and anticyclonic storms. These winds usually average at least 15 knots, gusting to 40 or 50 knots, and tend to blow obliquely to the shoreline. Thus, they have greater fetch over shallow water than winds blowing directly offshore.

Method of wind tide analysis.--When examining tide gage records for wind effects, I first drew a line of mean water level (MWL) that passed midway between high and low water levels on the tide curve. Normally the MWL line is horizontal, or at least straight. With high wind speeds, MWL rises or falls depending on wind direction. Wind speeds less than 20 to 25 knots do not seem to modify the astronomical tide curve on which the MWL line is based. For wind speeds above 20 to 25 knots the astronomical tide curve generally was distorted and MWL was harder to estimate. The highest MWL reached during the wind tide was subtracted from the initial MWL, that occurred prior to the onset of high wind speeds and wind tide effects, to get the meteorological tide. Finally barometric effects were subtracted from the meteorological tide to get the apparent wind tide. Where wind shift occurred from southerly to northerly winds, the MWL immediately prior to wind shift was taken as the initial MWL.

I compared the tide curves to weather data for Victoria, Texas, which is approximately 40 miles from Pass Cavallo. Wind speeds at Victoria generally correlate well with observed wind tides on the coast, although some wind tides (as noted) probably were caused by stronger winds. Victoria is about 100 feet above sea level so that barometric pressures might have been about 0.1 inches greater at the coast (Trewartha, 1954, p. 55).

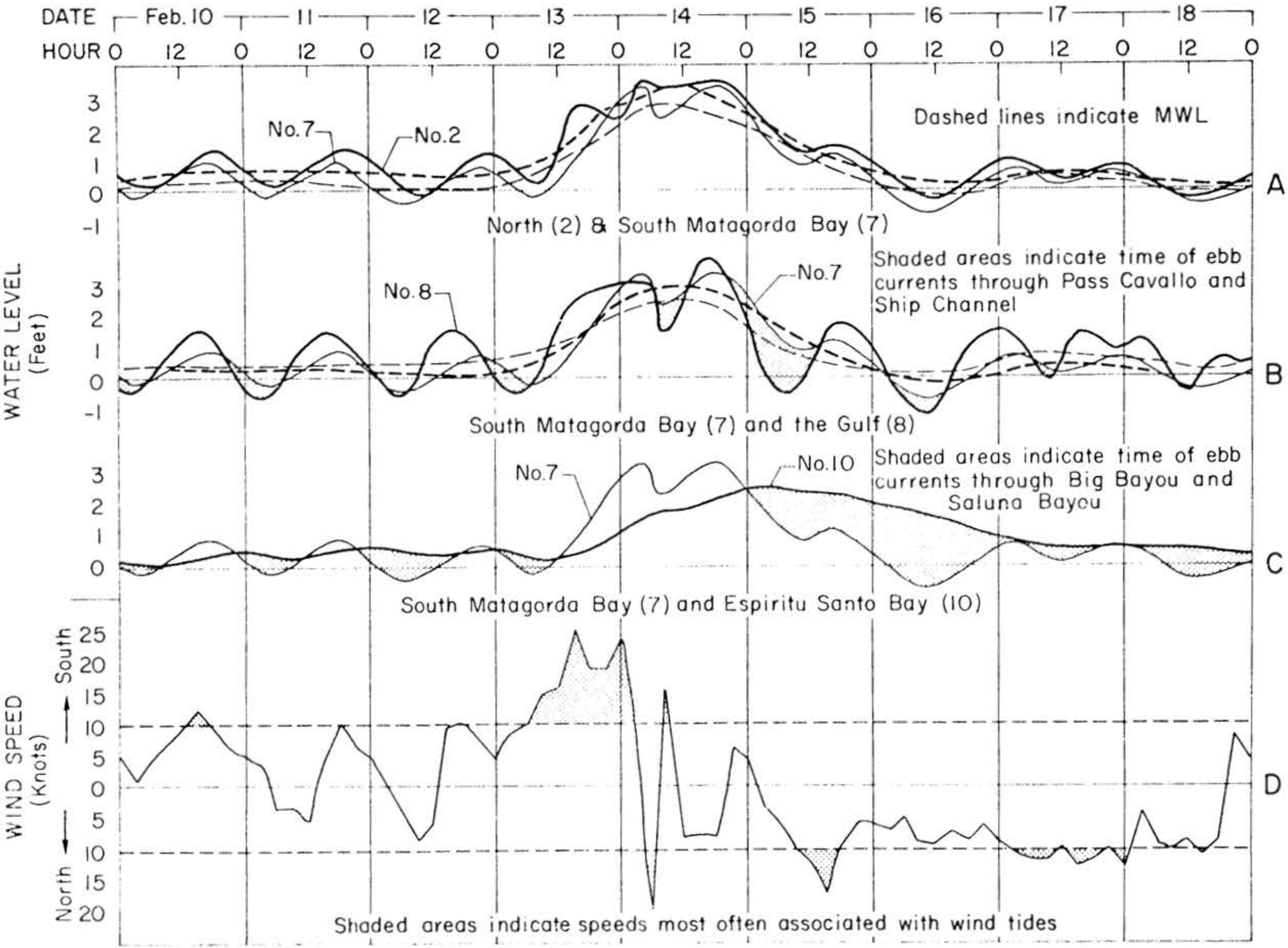
An extreme tide, February, 1969.--An unusually high wind tide occurred during February 13-15, 1969, associated with onshore winds (100-140 degrees) that had average speeds exceeding 15 knots for 12 consecutive hours. Figure 5 is a graphic picture of the tide curves at gages 2, 7, 8 and 10. A plot of wind speed against relative north or south direction is shown for comparison.

The actual wind tide began about noon on February 13th. Previously barometric pressure had fallen at Victoria from 29.9 inches on February 10th to 29.7 inches, due to an approaching cyclonic storm. Bay and Gulf water levels had remained steady with variable winds less than 10 knots. About 6:00 a.m., on February 13th wind speeds increased above 10 knots, reaching a peak average of 25 knots between noon and 3:00 p.m. About noon water levels began rising almost simultaneously in north Matagorda Bay and along the Gulf shoreline (Fig. 5-A and 5B). The tide curve in south Matagorda Bay shows a definite lag, in keeping with strong southerly winds depressing the water surface at that point.

Between 3:00 and 6:00 a.m., on February 14th, the wind shifted from SE to NE (30°) (Fig. 5-D). At the time of wind shift, MWL in the Gulf had risen about 1.7 feet above the MWL on February 12th and MWL in

Figure 5

Comparison of tide curves in Matagorda Bay, Espiritu Santo Bay, and the Gulf of Mexico during February 10 - 8, 1969. Relative wind speed and direction are shown below for Victoria, Texas.


DATE Feb. 10 11 12 13 14 15 16 17 18
HOUR 0 12 0 12 0 12 0 12 0 12 0 12 0 12 0 12 0 12 0
WATER LEVEL (Feet)
No.7
No.2
Dashed lines indicate MWL
A
North (2) & South Matagorda Bay (7)
No.8
No.7
Shaded areas indicate time of ebb currents through Pass Cavallo and Ship Channel
B
South Matagorda Bay (7) and the Gulf (8)
No.7
No.10
Shaded areas indicate time of ebb currents through Big Bayou and Saluna Bayou
C
South Matagorda Bay (7) and Espiritu Santo Bay (10)
WIND SPEED (Knots)
South
North
D
Shaded areas indicate speeds most often associated with wind tides

Matagorda Bay had risen about 2.5 feet (Fig. 5-B). As much as 0.3 feet of this rise probably is related to a low barometric pressure of about 29.6 inches recorded at Victoria. Normal sea level pressure is about 29.9 inches (Trewartha, 1954, p. 53). A wind tide of about 1.4 feet in the Gulf and 2.2 feet in the bay in 18 hours is impressive for those wind speeds. Probably wind speeds at the shoreline and in the Gulf were much greater than those recorded at Victoria. Also, the low center may have been centered in the Gulf, and moved landward, creating a situation similar to a diffuse tropical cyclone.

After wind shift, wind directions were variable (Fig. 5-D). During the first 3 hours wind speeds averaged 20 knots from the NE and water levels dropped _immediately_ at tide gages 2 and 7 in Matagorda Bay and at gage 8 in the Gulf. This drop in water level also coincides with the time of low water predicted in the Tide Tables so that the magnitude of response to wind alone is difficult to determine. Usually there is a lag of about 2 hours between high tide at gages 8 and 7, and also between gages 7 and 2. During the next 3 hour period, wind speeds averaged 15 knots from the east (90 degrees). Mean water level at all 3 gages remained high, some of which might be due to local flooding from heavy rainfalls (2.5 inches in 2 days at Victoria) that occurred on the 13th and 14th (U. S. Dept. of Commerce, 1966-1970: February 1969). The astronomical high tide, superimposed on this high MWL, peaked the Gulf high water mark nearly 4 feet above datum and almost 2 1/2 feet above the previous astronomical high tide mark on February 12th. Although this Gulf peak was the highest recorded during this wind tide, water levels in Matagorda Bay were higher than those in the Gulf before wind shift occurred (Fig. 5-C).

Water levels in Matagorda Bay and in the Gulf fell off steadily for the next 24 hours after noon on February 14th, until they had reestablished nearly the same level as on February 12th. Currents through Pass Cavallo and also the ship channel probably followed the pattern shown in Figure 5-B, the shaded areas indicating times of ebb currents out of Matagorda Bay. Notice that there is a tendency for flood currents into Matagorda Bay to occur with southerly winds, and ebb currents following wind shift to occur with falling water level. Water level in Matagorda Bay stayed slightly lower than on February 12th for the next 3 days, February 16-18, due to north winds averaging about 10 knots. The Gulf MWL, however, had recovered so that flood currents predominated.

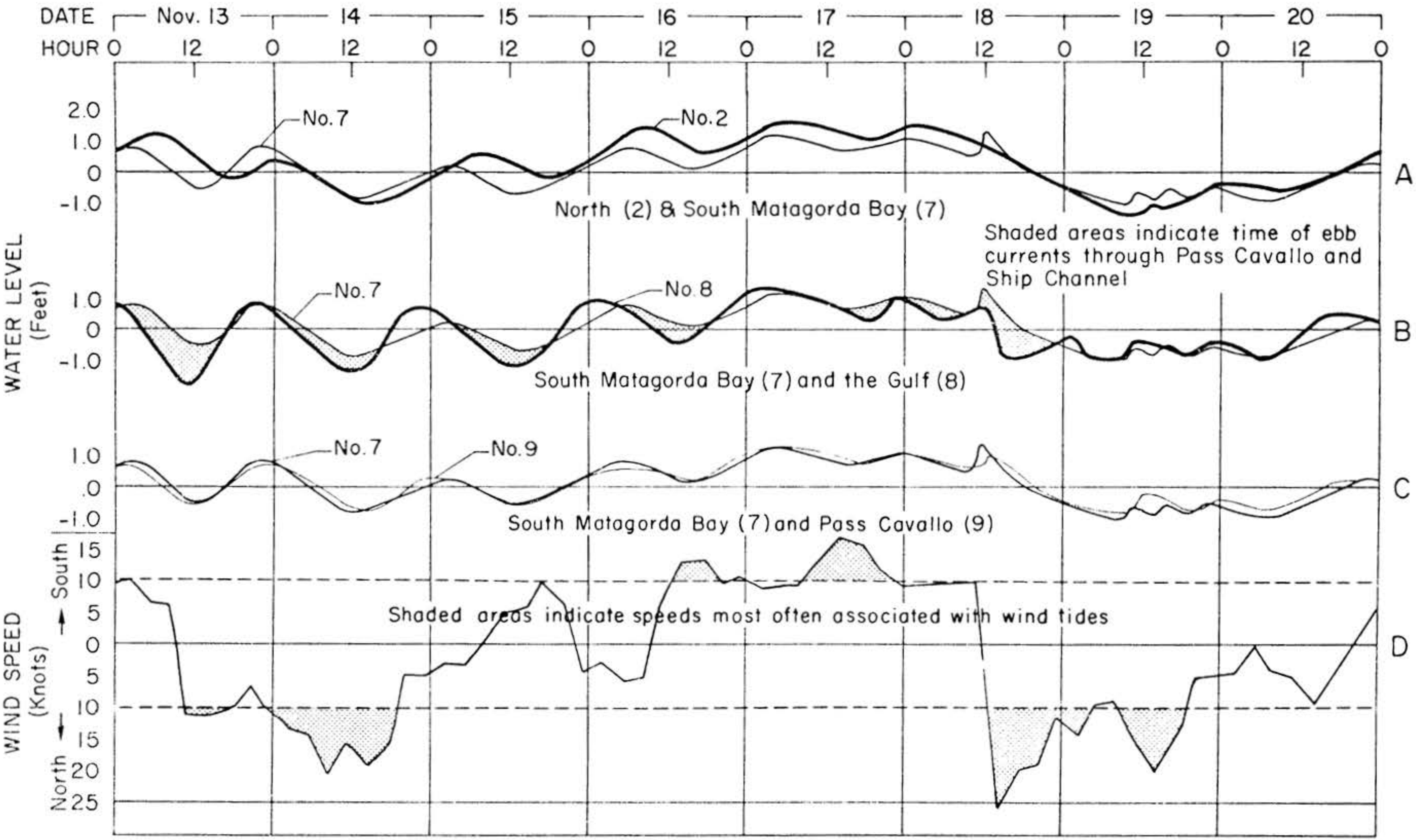
The hydraulic relationship between Espiritu Santo Bay and Matagorda Bay also is shown in Figure 5-C. Peak water level in Espiritu Santo Bay occurred about 6 hours after peak high tide in south Matagorda Bay. Almost no irregularities show up on the tide curve for gage 10. The wind shift on February 14th is marked as a flattening in the otherwise uniform rise of water level. Ebb currents apparently were continuous into Matagorda Bay for four days following highest water level. Hydraulically Saluria Bayou and Big Bayou appear to be distinct tidal channels and not directly a part of the channel pattern of Pass Cavallo.

<u>The typical winter pattern</u>.--Three separate wind tides are shown in Figure 6. On all tide gages, mean water levels fell with northerly winds and rose with southerly winds. This undulating pattern is fairly typical for the cooler months. Diurnal tides occurred through the 18th, and then semi-diurnal tides. Distortion of the astronomical tide curve is noted especially with strong north winds during the period of semi-diurnal tides (Nov. 18-20).

Figure 6-C compares the tide curves at gage 7 in south Matagorda Bay near the ship channel and at gage 9 in Saluria Bayou at Pass Cavallo. Except that they are slightly out of phase, these records are

Figure 6

Comparison of tide curves in Matagorda Bay, Pass Cavallo, and the Gulf of Mexico during November 13 - 20, 1969. Relative wind speed and direction are shown for Victoria, Texas.


DATE Nov. 13 14 15 16 17 18 19 20
HOUR 0 12 0 12 0 12 0 12 0 12 0 12 0 12 0 12 0
WATER LEVEL (Feet)
No. 7
No. 2
North (2) & South Matagorda Bay (7)
A
Shaded areas indicate time of ebb currents through Pass Cavallo and Ship Channel
No. 7
No. 8
South Matagorda Bay (7) and the Gulf (8)
B
No. 7
No. 9
South Matagorda Bay (7) and Pass Cavallo (9)
C
WIND SPEED (Knots)
South
North
Shaded areas indicate speeds most often associated with wind tides
D

remarkably similar--the discrepancies well within the limitations of the gages. Because of this similarity, tide curves at gage 7 were used to estimate current directions in Pass Cavallo when records for gage 9 were not available.

Normally mean water level in north Matagorda Bay (gage 2) is higher than in south Matagorda Bay (gage 7) (see Fig. 5-A and Fig. 6-A). Southerly winds slightly increase the difference between MWL at gages 2 and 7, although the rise in MWL is almost exactly the same at both gages. With northerly winds, however, mean water level at gage 2 tends to approach MWL at gage 7, and with the strongest winds to fall below MWL at gage 7. Thus, the magnitude of wind tide for southerly winds tends to be uniform throughout Matagorda Bay, and much greater in the northern part with northerly winds.

Pass Cavallo and also the ship channel serve as effective tidal drains during northers and prevent water from piling up against the southern shore of Matagorda Bay. The falling tide curves at gage 7 in southern Matagorda Bay and at gage 8 in the Gulf overlap almost exactly during November 17-20 (Fig. 6-B). This indicates that ebb currents through Pass Cavallo and the ship channel probably were continuous to keep up with the large volume of bay water driven south and falling sea level. The "blip" on the tide curve at gage 7 may be a brief rise due to the rapidly moving cold front before Matagorda Bay water began emptying through Pass Cavallo. On November 19th, two blips occur on tide curve 7 and one on tide curve 2 that are about 2.4 hours out of phase and about 0.5 feet high (Fig. 6-A). These blips probably represent a seiche, or standing wage in Matagorda Bay, initiated by the brief increase in wind speed to 20 knots. That these blips die out quickly is probably a function of dampening through Pass Cavallo and other smaller basins connected to Matagorda Bay. Usually only one high and low were given in the tidal data, so that other seiches probably were not recorded.

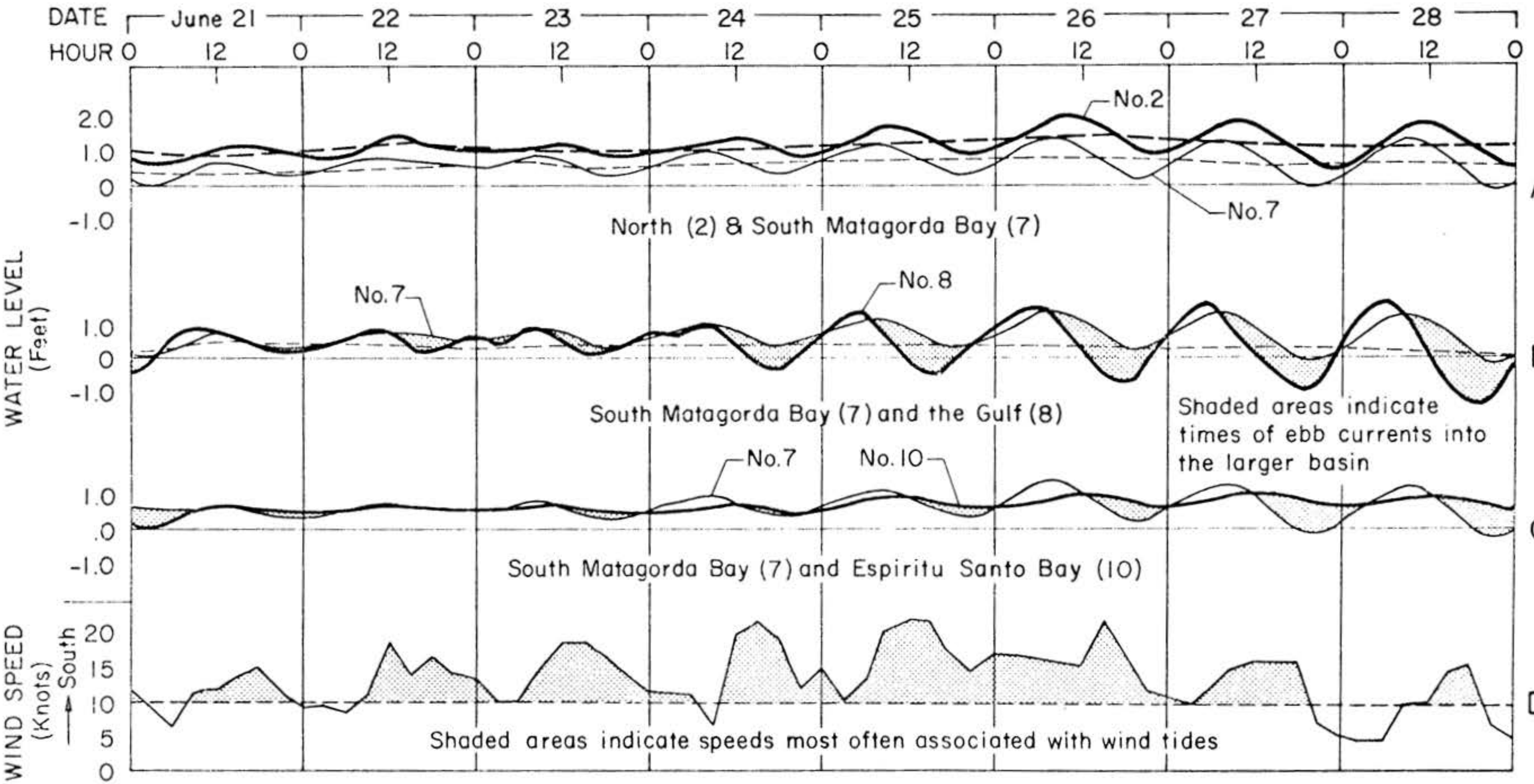
In order to see if these observations were reasonable for a standing wave with a single node ($n = 1$) in Matagorda Bay, I used "Merian's formula," which gives the natural period (T) of a basin in terms of its length (L) and depth (d):

$$T = \frac{2\,L}{n\sqrt{gd}}$$ (Mason and Sorensen, 1971, p. 60; Ippen, 1966, p. 287)

Normally a basin the shape of Matagorda Bay would have nodes for each long axis. However, because winds

Figure 7

Comparison of tide curves in Matagorda Bay, Espiritu Santo Bay, and the Gulf of Mexico during June 21 - 28, 1969. Relative wind speed and direction are shown for Victoria, Texas.



DATE
June 21
22
23
24
25
26
27
28
HOUR
0
12
No.2
No.7
2.0
1.0
0
-1.0
A
North (2) & South Matagorda Bay (7)
WATER LEVEL (Feet)
No.7
No.8
B
South Matagorda Bay (7) and the Gulf (8)
Shaded areas indicate times of ebb currents into the larger basin
No.10
C
South Matagorda Bay (7) and Espiritu Santo Bay (10)
WIND SPEED (Knots) South
20
15
10
5
D
Shaded areas indicate speeds most often associated with wind tides

from NNE (10 degrees) initiated the seiche, I assumed that oscillations occurred only along the longer NE axis ($L = 15$ miles). The average depth of Matagorda Bay (d) is about 12 feet. Using these values, $T = 2.25$ hours. This is almost exactly the observed period of 2.4 hours and close enough to suggest that seiches do occur in Matagorda Bay, even if briefly.

The summer pattern.--Almost 8 continuous days of southerly winds with speeds at least 10 knots are shown in Figure 7. During this interval MWL in the Gulf of Mexico remained level, only falling slightly on the 28th (about 0.2 feet). This slightly lower MWL is coincident with a rise in barometric pressure from 29.6 on the 25th to 29.9 on June 28th and especially with wind speeds less than 10 knots that might have reduced wind setup. Even so the response is sluggish compared to wind tides during the cooler months.

Throughout these 8 days, mean water level in Matagorda Bay remained about 1.0 foot higher at gage 2 than at gage 7 (Fig. 7-A). There was a slight rise of about 0.4 feet at both gages from June 24th through June 26th associated with wind speeds reaching almost 20 knots each day during the late afternoon. Even so the rise in water level is steady for these 3 days and not undulating with wind speed.

Figure 7-B shows that from June 24th through the 28th ebb currents dominated in Pass Cavallo. This probably is due to strong southerly winds holding a larger volume of water in Matagorda Bay. Note that during semi-diurnal tides, June 21-23, currents through Pass Cavallo probably were weak or non-existent, allowing shoaling to occur at the Gulf bar.

For 3 days, June 21-23, there were practically no currents through Big Bayou and Saluria Bayou (Fig. 7-C). Then as the diurnal tidal range increased, currents picked up, until for June 27-28, ebb currents apparently dominated over flood currents.

Tides and currents in Pass Cavallo and vicinity are relatively uneventful during the Summer. Apparently the tendency for ebb currents to be enhanced during Summer by strong southerly winds holding water in Matagorda Bay counteracts the tendency for the inlet to shoal at the Gulf bar during the semi-diurnal tides (neap tides) each month.

Tropical Storm and Hurricane Tides

Tropical cyclones originate in the intertropical latitudes of the Atlantic Ocean, Caribbean and Gulf of Mexico. These storms are several hundred miles in diameter with counterclockwise wind circulation that increases in speed towards the center, or eye, of the storm. Hurricanes belong to the most intense class of tropical cyclones and have the lowest barometric pressures and wind speeds of 74 mph or more (Leipper, 1954, p. 96).

Tropical cyclones of both hurricane, and lesser intensity (tropical storms), are important to coastal areas because their energy is of catastrophic proportions. A hurricane moving inland on the Texas coast is accompanied by a storm surge near the center of between 6 and 15 feet, steep wind-driven waves over 10 feet high, and high rainfall, sometimes in excess of 15 inches (Hayes, 1967). In Texas, hurricane season occurs from June to November, with over half of all storms occurring in August and September (Price, 1956b). An average of one hurricane will strike the Texas coast every 2 - 2.5 years. Effects of these storms on Texas coastal environments have been discussed by Andrews (1966, 1970), Carr (1967), Hayes (1964a and b, 1965, 1967), McGowen, et al. (1970), Prentiss (1951), Price (1956a and b), and Scott, et al. (1969).

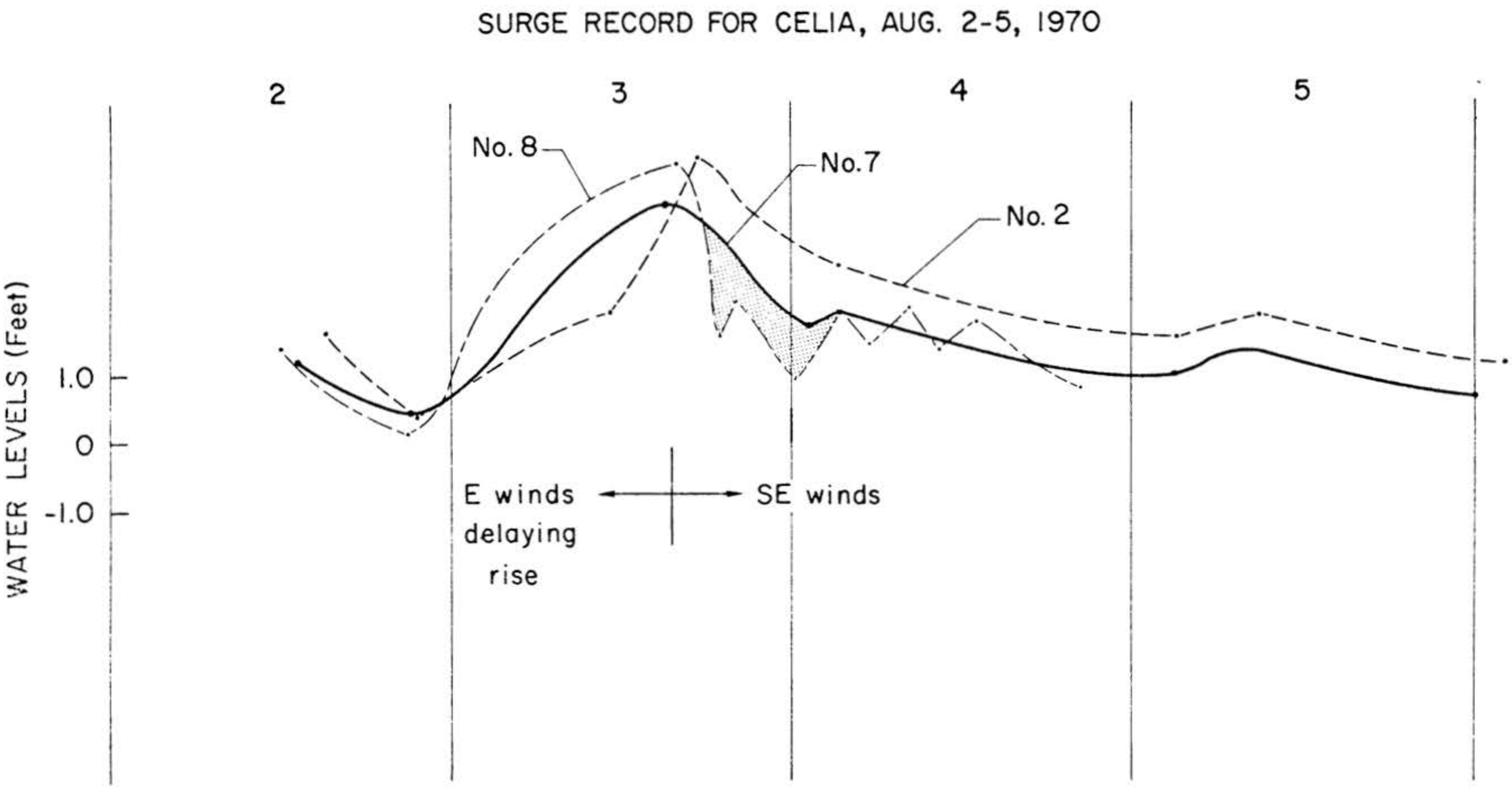
Effects of hurricanes on large tidal inlets have not been prominent, probably because they occur infrequently. Also very little is known about the interaction of surge and wind tides generated in Texas bays and lagoons by tropical cyclones. Generally, tides are higher in bays and at the Gulf shoreline, to the east or right of the storm center due to wind setup by hurricane-force winds blowing onshore (Hayes, 1967; McGowen, et al., 1970). Tide gage records that were available for Pass Cavallo and Matagorda Bay include a partial surge history of two hurricanes: Beulah, September 18-23, 1967, and Celia, July 30-August 5, 1970, (Appendix A). Both of these hurricanes struck the Texas coast south of the study area so that winds near Pass Cavallo were from southeast and east, and less than 30-40 mph (U.S. Dept. of Commerce, 1966-1970: September 1967 and August 1970). The maximum Gulf surge for Beulah was 5.2 feet at gage 9 in Pass Cavallo, and for Celia was 4.2 feet at gage 8 on the Gulf jetty at the Matagorda Ship Channel (Fig. 2). Neither of these storm tides overtopped the barriers adjacent to Pass Cavallo.

Hurricane Beulah went ashore near Brownsville, Texas, about noon on September 20, 1967. Tides rose for about 1 1/2 days before the eye passed inland and then fell for 2 days. Ebb currents may have persisted in Pass Cavallo's channels for the entire two days of falling tide to transport material out of the pass that had been brought in during the rising tide. Winds at Victoria were easterly between 10-30 knots during this period so that the ebb probably was not retarded by winds. Brown Cedar Cut, a small inlet about 40 miles north of Pass Cavallo (Fig. 2), was re-opened by ebb currents generated during Beulah's tide (Mason and Sorensen, 1971).

Hurricane Celia in August 1970 moved across the Gulf of Mexico in less than 2 days. The maximum Gulf surge of 4.2 feet occurred about 10 hours after the astronomical high tide of 2 feet on August 3, 1970, but fell abruptly to 1.6 feet during the next 3 hours (Fig. 8). Tide levels during the next 24 hours oscillated at 2-3 hour intervals, between 1 and 2 feet above MSL (datum established by the U.S. Corps of Engineers). These oscillations are not typical of normal tidal fluctuations and suggest that a "seiche," or standing wage, had been generated temporarily in the Gulf of Mexico by this rapidly moving storm (Fig. 4).

Figure 8

The surge record at Matagorda Bay for hurrican Celia, August 2 - 5, 1970. Between 8 AM and 3 PM on August 3rd winds at Victoria, Texas, were from the east at speeds exceeding 20 knots, delaying rise of WL's at gage 2. From 3 PM on August 3rd to 6 PM on August 4th winds were from the southeast between 15 and 25 knots, so that wind setup peaked the surge to 4.3 feet at gage 2.


SURGE RECORD FOR CELIA, AUG. 2-5, 1970
2
3
4
5
No. 8
No. 7
No. 2
WATER LEVELS (Feet)
1.0
0
-1.0
E winds delaying rise
SE winds

The surge record for Celia in Matagorda Bay at gages 7 and 2 is given in Figure 8. Comparison of the records at gage 8 in the Gulf and at gage 7 just inside the ship channel indicates that flood currents were continuous in Pass Cavallo and the ship channel during the first 18 hours of August 3rd. Gage 2 in the northeast part of Matagorda Bay shows a slower rise than at gages 7 and 8. This slow rise coincides with easterly winds, with speeds greater than 20 knots, retarding rising water level on the east side of the bay (U.S. Dept. of Commerce, 1966-1970: August 1970). The wind shifted to southeast with the arrival of the maximum surge in the Gulf, but did not reduce in intensity. The tide peaked higher at gage 2 than at gage 7 due to setup by these relatively strong winds. Water level remained higher in northern Matagorda Bay for several days due to southeast winds greater than 15-20 knots holding water in the bay. Apparently ebb currents in Pass Cavallo lasted for less than 12 hours after the surge peaked, and during August 4th there was very little current activity in either direction because the Gulf remained between 1-2 feet above mean sea level. The combination of flood dominance during the surge, moderate wave activity and the slow draining of Matagorda Bay through the 5th, probably kept the entrance shoaled for several days at Pass Cavallo.

River Flooding

River discharge is potentially a source for additional head in Matagorda Bay to enhance ebb currents through Pass Cavallo. Before 1935, two large rivers, the Colorado and Lavaca Rivers, and many small local creeks drained into Matagorda Bay (Fig. 2). After 1936, the Colorado River was dredged to discharge directly into the Gulf of Mexico (Wadsworth, 1966).

Examination of stream gaging records (Patterson, 1965, U.S. Govt. Survey, 1970) for the lower Lavaca and Colorado Rivers indicates that, except during floods, the combined daily discharges of these two rivers would have been less than 10,000 cubic feet/sec. This would add less than 0.1 foot of water over the surface of Maragorda Bay in 12 hours, or half the tidal period (Marmer, 1954). About 0.1 foot of head would not add significantly to ebb currents through Pass Cavallo. Even floods with discharges of about 30,000 cubic feet/sec. that occurred about every 2 years on the Colorado River and about every 10 years on the Lavaca River would have added only about 0.2 feet of water over the surface of Matagorda Bay if continuous for 12 hours. The times of peak discharges on these rivers usually do not coincide because of differences in drainage basins and rainfall distribution. Sometimes flooding is confined to only one river. Thus, river discharges normally are not large enough to influence equilibrium conditions at Pass Cavallo.

Apparently only river floods of infrequent catastrophic proportions are able to affect tidal discharge through Pass Cavallo. Before about 1937, when dams were begun on the Colorado River above Austin, the Colorado River had flood discharges exceeding 80,000 cubic feet/sec. about every 10 years. Flood discharges of this magnitude occurred even less frequently on the Lavaca River. This much water continuously discharged for 12 hours would have added at least 0.5 foot of head over the surface of Matagorda Bay. Catastrophic flooding on the Lavaca and Colorado Rivers, occurring within a few days of each other, might have enhanced ebb currents through Pass Cavallo for several days.

The building of dams on the Colorado River above Austin, Texas, between 1935 and 1940, reduced the frequency of peak floods exceeding 80,000 cubic feet/sec. They now occur about every 20 years or more (Patterson, 1965). Thus, the possibility of river discharge influencing Pass Cavallo's currents is even more remote, even though the Corps of Engineers plans to divert the flow back into Matagorda Bay (J. H. McGowen, 1972, personal communication).

Flooding and heavy rainfalls tend to be seasonal. Average monthly and maximum rainfalls for different coastal cities are published in the Texas Almanac and State Industrial Guide (The Dallas Morning News, 1970). These records indicate that extreme rainfalls and floods on the Texas coast are associated with hurricanes and northers. For example, local rainfalls of about 9 inches in 24 hours occurred with frontal thunderstorms from Freeport to Corpus Christi during February 1969 (U.S. Dept. of Commerce, 1969). Also, local rainfalls of more than 20 inches have occurred with several hurricanes (Scott, et al., 1969). The largest monthly average rainfalls (greater than 3.5 inches) at Galveston with 92 years of record occurred during hurricane season, July through September, and during peak norther "season," November through January (The Dallas Morning News, 1970). At Port Lavaca and Matagorda (Fig. 2) with about 30 years of record, monthly rainfalls greater than 3-3.5 inches occurred in October, December, April and May, and from July through September.

Even though river discharge is not an important source of additional head in Matagorda Bay, Simmons and Hoese (1959, p. 67) noted that Cedar Bayou, a small inlet south of Pass Cavallo, tended to close during droughts when river flooding was minimal (Fig. 1). Maximum discharges on the Guadalupe River near Cedar Bayou may occur even less frequently than on the Colorado or Lavaca Rivers because the climate is more arid southwestward. The tendency for Cedar Bayou to shoal and close during droughts may be related to the frequency of cyclonic and anticyclonic storms passing through Texas during the cooler months. Drought years in Texas are associated with either more or less cyclonic storms than during wet years (Carr, 1966). With fewer of these storms the number of days of wind tides would be reduced, and with more the number of consecutive days and thus the magnitude of wind tides might be reduced.

Inlet Currents

The Gulf of Mexico has a greater range in tide than Matagorda and Espiritu Santo Bays. Consequently, it is the Gulf that initiates hydraulic currents through Pass Cavallo. Although no detailed study of tidal currents has been made in Pass Cavallo, speeds normally are "believed to reach 2 knots," or about 3.2 feet/sec., and currents may attain 3 knots through the Matagorda Ship Channel (U.S. Coast and Geodetic Survey, 1967, p. 187). Probably ebb currents are stronger than flood currents for most of the year. At Galveston Entrance, between the jetties, ebb currents dominate over flood currents, so that the average on flood is 1.7 knots (maximum) and on ebb 2.3 knots (maximum) (U.S. Coast and Geodetic Survey, 1967, p. 173). Since the Gulf tidal range varies during each month from about 3.0 feet (spring tide) to about 0.8 feet (reap tide), the daily speeds reached by inlet currents also vary.

Wind tides occur year round but especially during the cooler months, September-May. The most important effect of these water level changes occurs when they enhance ebb currents through inlets. The actual current velocities during wind tides at Pass Cavallo are unknown. However, the possibility that current velocities or duration of currents is increased is great. Consider that more water empties from Matagorda Bay through Pass Cavallo during a norther because water is driven southward if the Gulf is also lower than normal. Should a norther occur during semidiurnal tides, inlet currents might not reverse but continue to empty Matagorda Bay until the wind direction shifted. Current directions at Aransas Pass also tend to be in the direction of stronger winds (Price, 1952, p. 251; Shepard and Moore, 1960, Fig. 6, p. 123).

Strong southerly winds during the cooler months tend to raise both bay and Gulf water levels. Flood currents and wave activity during this time would be strong and the sediment load of inlet currents would be large. Generally, northers follow close behind periods of strong south winds. During summer, wind tides of about 0.5 foot occur in Matagorda Bay, but not in the Gulf, when winds are especially strong during the afternoon between noon and 6 PM. When this occurs for several days, the volume of water slowly increases in Matagorda Bay and ebb currents become much stronger than flood currents because the bay level is higher than normal at low tide in the Gulf. This helps to counteract shoaling from increased wage action on the Gulf bar produced by strong southerly winds, and also some summer hurricanes. The U.S. Coast and Geodetic Survey (1967, p. 187) also notes that following a period of strong southerly winds, ebb currents sometimes are especially strong through the Matagorda Ship Channel (and also, no doubt, through Pass Cavallo).

Catastrophic events, such as river floods and hurricanes occur too infrequently to affect equilibrium conditions at Pass Cavallo. When hurricanes do occur the combination of surge and heavy wave activity increases the sediment load of inlet currents.

Storm winds, decreasing in intensity from the center, produce wind setup in bays. Inlet currents will be affected in many ways by hurricanes depending on where the storm strikes the shoreline. At the time and place of direct hit, the surge generally overtops the barriers so that water disperses randomly and is not necessarily confined to inlet or surge channels. Hurricane discharges at tidal inlets will be greater than those generated by the astronomical tide if the rising and falling tide is greater than the spring tidal range, or about 3 feet, for more than the tidal period or about 25 hours. Tropical cyclones have not been known to significantly change large Texas inlets, although widening and shoaling at small Texas inlets have been attributed to hurricanes (Price, 1947, Mason and Sorensen, 1971, p. 44). Excessive shoaling in inlets may occur if the ebb flow is not as strong as the flood for any of the following reasons: (1) Other inlets or surge channels have opened to the tidal basin so that the ebb is distributed through many openings. (2) Onshore winds to the east of the storm center slow draining of the bay to reduce ebb velocities. (3) The surge rose and fell too rapidly for much water to enter the tidal basin to generate ebb currents. Offshore winds west of the storm center lower sea level rapidly and thus increase ebb current velocities. Scouring during ebb flows tend to dominate to the west of the eye (Hayes, 1967).

Thus, the astronomical tide and wind tides must determine equilibrium conditions at Texas tidal inlets. Wind tides especially seem to enhance ebb currents to remove littoral drift material from the channel. During droughts, wind tides may be either less frequent, or of reduced effectiveness because cyclonic and anticyclonic storms pass through too quickly. Without the additional flushing action provided by wind tides, shoaling might be excessive at Texas inlets from heavy wave action on the Gulf bar during neap tides and some hurricanes.

STABILITY OF THE CHANNEL SYSTEM AND INLET SHORELINES

Two independent variables, littoral drift and tidal discharge, primarily determine whether or not an inlet attains a state of long-term dynamic equilibrium, or stability (Brunn and Gerritsen, 1960, p. 7). Littoral drift rate is a function of the wind and wave regime on a coastline, and as such is independent of the inlet environment. Tidal discharge is determined by the dimensions of the tidal basin and tidal range along the coastline, both of which limits the tidal discharge possible through an inlet. Yet in spite of these restrictions on discharge, natural tidal inlets studied on European and American coastlines tend to have in common a small range of current velocities through stable cross-sections (Brunn and Gerritsen, 1960; Brunn, 1966).

Brunn and Gerritsen (1960) note that there are two types of inlet stability. Natural inlets tend to exhibit geometric stability in terms of entrance cross-section, and geographic stability in terms of lateral migration. Both geometric and geographic stability are interrelated and a change in one often leads to a change in the other.

In this study I have included the following under the heading of geometric stability: channel pattern, channel length and the distribution of inlet deposits related to the channel pattern. These aspects of an inlet's geometric stability are also intimately related to tidal discharge and littoral drift rate.

Geometric Stability

Computing the instantaneous tidal discharge is fairly complex and requires measurements of current velocities or tidal differentials, and a contemporary cross-section. A simpler but less accurate method, useful to compare old charts, for which there is no velocity data, is to assume that the tidal basin fills everywhere at the same time, has a uniform tidal range, and that flood and ebb currents have about the same velocity. Then, tidal discharge is computed as follows,

$$Q = \frac{2\ h\ a}{T},$$

where h = tidal range in the tidal basin, a = area of the tidal basin, and T/2 = one-half the tidal period (T = 25 hours, Mason and Sorensen, 1971, p. 68). The subsequent configuration of Matagorda Bay and the almost identical tidal ranges at gages 2 and 7 indicate that this bay is fairly well suited to these assumptions.

Since Pass Cavallo receives a small part of its tidal discharge from Espiritu Santo Bay, I calculated the tidal prism ($\Omega_2 = h_2 \cdot a_2$) for that basin and added it to the tidal prism for Matagorda Bay (Ω_1) to get the tidal discharge through Pass Cavallo. For simplicity, I assumed that the entire area of Espiritu Santo Bay was involved instantaneously in the tidal exchange with Pass Cavallo. Actually the tidal prism of Espiritu Santo Bay thus calculated may be too large by at least twice, but it is also small relative to Matagorda Bay (Appendix C). Thus, the complete equation used to calculate V and to compare Pass Cavallo for cross-sectional area stability since 1856 was,

$$V = \frac{2\ (\Omega_1 + \Omega_2)}{T\ A}\ .$$

The same approach was used to calculate tidal discharge for Galveston Entrance in 1867. I used the entire area of West Bay together with Galveston Bay to compute the average maximum velocity through Galveston Entrance of 2.78 ft/sec (Appendix C), which falls within the range of velocities common at inlets on diurnal coasts (Brunn, 1966). However, at any one time only half of West Bay probably is connected tidally to Galveston Entrance, because a fairly small tidal inlet, San Luis Pass, is located at the southern tip of West Bay. The relationship of these smaller tidal basins to Galveston Entrance and to Pass Cavallo is hydraulically complex but relatively insignificant, due to their small size. The discrepancy between current velocities computed using the entire area of the smaller tidal basins versus using only part of the area may represent the contribution of streams and rivers to the inlet discharge.

Areas of bays were determined by cutting out bay outlines traced from Coast Chart 1117 and weighing them on an analytical balance to the nearest hundreth of a gram. Bay weights were then compared to the weight of a 10-mile square on the same paper. Results were calculated in square feet.

Entrance cross-sections at Pass Cavallo were located at the narrowest part of the inlet between the barriers where flood and ebb channels converged. The line of cross-section was oriented perpendicular to flow in the axial trough from Matagorda Island to Pelican Island, and then perpendicular to flow in channels on the Gulf bar from Pelican Island to Matagorda Peninsula. Care was taken to position the cross-section at the same location relative to channels and barriers on each chart.

At Galveston Entrance, the entrance cross-section was located at the narrowest point between the barriers and just seaward of where the Galveston Channel joins the axial trough.

Pass Cavallo has passed through three distinct phases since 1856. Pass Cavallo was, until about 1930, the only large tidal opening to Matagorda Bay, the second largest bay on the Texas coast. Between 1929 and 1935 the Colorado River rapidly built a delta across the east arm of Matagorda Bay (Wadsworth, 1966). This event reduced the tidal area of Matagorda Bay by 1.8 billion square feet and the mean tidal discharge through the pass by about 44,000 cubic feet/sec. (Appendix C). By 1934 Pass Cavallo had stabilized with respect to this new discharge. Between 1935 and 1952, a small inlet opened 11 miles north of the pass and in 1965 the Matagorda Ship Channel was opened through Matagorda Peninsula (Fig. 2). These events reduced the tidal discharge even more.

The U. S. Coast and Geodetic Survey ceased to chart the pass about 1960--probably because ship channel construction was in progress. Data on Pass Cavallo in 1971 was estimated from NASA high-altitude color photographs and from 1971-1972 edition of Coast Charts. Calculations are given in Appendix B.

For comparison, I have included data on two other natural Texas inlets: Galveston Entrance, which in 1867 was larger than Pass Cavallo, and Brown Cedar Cut that in 1971 was much smaller (Fig. 1 and 2). For all three inlets the magnitudes of wind, tides and even bed materials are similar. Shepard (1960, p. 209) notes that most Texas barrier and nearshore areas (less than 12 feet deep) have median sand sizes between .125 and .25 mm., and that Gulf and bay shells are concentrated on the beds of active inlets. The action of waves out of the Gulf or in large Texas bays probably cause shells to be entrained by inlet currents that normally would not move them. Thus, shell would be concentrated on beds of inlet channels as the competence of inlet currents to move shell decreased away from the zone of wave action.

Area of Entrance Cross-section.--Brunn (1966) found that most tidal inlets that engineers had studied in Europe and America had average maximum current velocities (V) of about 1.0 meter/second or 3.2 feet/second. Inlets on coasts with semidiurnal tides had slightly faster current velocities than 3.2 feet/second and inlets on coasts with diurnal tides slightly slower. At Galveston Entrance, tides are mostly diurnal and the average maximum velocity between the jetties is about

Table 1. Stability of cross-sectional area with respect to velocity and tidal discharge at spring tides. Values in parentheses are for mean tidal range.

	V_{max} (V) in ft/sec	Q_{max} (Q) in cu.ft/sec	A in sq.ft.
Pass Cavallo 1856	4.2 (3.06)	3.76×10^5 (2.74×10^5	8.945×10^4
1874	5.14 (3.89)	"	7.04×10^4
1887	4.3 (3.12)	"	8.8×10^4
1934	4.1 (3.02)	3.14×10^5 (2.3×10^5)	7.63×10^4
1965	4.4 (3.1)		7.15×10^4
1971	4.2 (3.1)	2.0×10^5 (1.58×10^5)	5.2×10^4
Galveston Entrance 1867	3.8 (2.78)	5.5×10^5 (4.0×10^5)	14.5×10^4
Brown Cedar Cut 1971	4.35 (3.22)	0.106×10^5 (0.08×10^5)	0.248×10^4

2.0 knots or 3.2 feet/second. Ebb currents at Galveston are faster than flood, being about 2.3 knots on ebb and 1.7 knots on flood (U. S. Coast and Geodetic Survey, 1967, p. 173). This small range of current velocities at inlets with different tidal ranges and discharges indicates that there is a dynamic equilibrium at tidal inlets between tidal discharge, Q, and the entrance cross-sectional area, A, illustrated by this fundamental hydrodynamic equation:

$$V = \frac{Q}{A} .$$

Current velocities determined by this equation are not instantaneous velocities, but rather an average of the fastest (maximum) currents during flood and ebb. Values for tidal discharge and consequently velocity will vary depending on the range of tide used. Table 1 shows average maximum velocities at flood or ebb (V), tidal discharge (Q), and cross-sectional areas (A) for Pass Cavallo, Galveston Entrance and Brown Cedar Cut. Discharges and velocities at spring tides (Q_{max}, V_{max}) and at mean diurnal tides (Q, V) are given to illustrate the range of the most frequent significant velocities and discharges at these inlets. Most of the time mean velocities and discharges would occur, but during spring

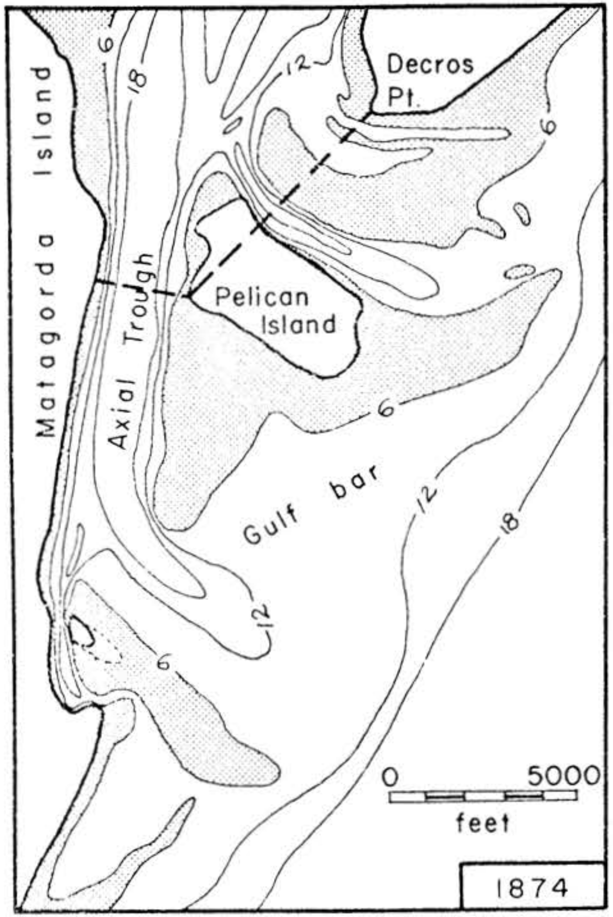
Current velocities determined by this equation are not instantaneous velocities, but rather an average of the fastest (maximum) currents during flood and ebb. Values for tidal discharge and consequently velocity will vary depending on the range of tide used. Table 1 shows average maximum velocities at flood or ebb (V), tidal discharge (Q), and cross-sectional areas (A) for Pass Cavallo, Galveston Entrance and Brown Cedar Cut. Discharges and velocities at spring tides (Qmax, Vmax) and at mean diurnal tides (Q, V) are given to illustrate the range of the most frequent significant velocities and discharges at these inlets. Most of the time mean velocities and discharges would occur, but during spring tides twice a month, and during wind tides and some tropical cyclones the higher values probably apply. Discharges larger than at spring tides may occur temporarily with hurricane tides greater than about 4 feet above mean sea level, but only infrequently.

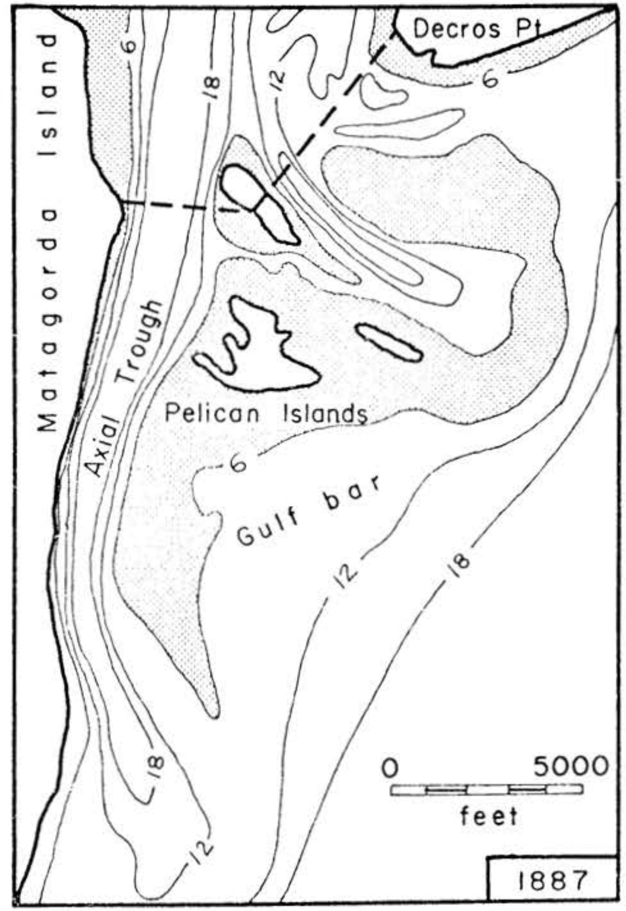
If Pass Cavallo were exhibiting a long-term equilibrium or stability between cross-sectional area and tidal discharges, then the computed velocities for Pass Cavallo would be identical for all 6 years. And computed velocities are nearly the same except for the pass in 1874. Values for Pass Cavallo in 1965, however, may be slightly high. In October, 1965, the Matagorda Ship Channel was partly dredged so that discharge through Pass Cavallo very likely was somewhat less than that shown in Table 1.

In May and June, 1874, the distribution of channels and shoals on the Gulf bar at Pass Cavallo was different than on any other chart or photograph of the inlet. The cross-sectional area of the axial trough and of the shoals east of Pelican Island were smaller, and the shoals less than 6 feet deep larger, than at any other time before 1965. The area of Pelican Island in 1874 was about 12.5 million square feet, and in 1856 and 1887 about 7 or 8 million square feet (Fig. 9). The reduction in entrance area shown in Table 1 could have been produced by a reduction in tidal discharge, and by shoaling by long-period, flat constructive waves (King, 1969, p. 250). There is no evidence on any of the old charts that the discharge was reduced because Matagorda Bay had another large tidal inlet during this time, or had a smaller area. However, the frequency of large tidal discharges may have been reduced slightly by severe droughts occurring in the early 1870's that would have reduced the number and intensity of wind tides. Droughts in the midcontinent tend to occur at 20-year intervals and the first severe drought for which rainfall

Figure 9

The Gulf bar at Pass Cavallo in June 1874 and in July 1887. The entrance area at the cross-section line was 70,400 square feet in 1874 and 88,000 square feet in 1887. The smaller cross-sectional area in 1874 corresponds with large areas of shoals, less than 6 feet deep, on the Gulf bar, and the large, subaerial Pelican Island. Pelican Island had a surface area of about 12.5 million square feet in 1874 and all three islands about 7 million square feet in 1887.


Matagorda Island
Decros Pt.
Axial Trough
Pelican Island
Gulf bar
6
12
18
0 5000
feet
1874


Matagorda Island
Decros Pt
Axial Trough
Pelican Islands
Gulf bar
6
12
18
0 5000
feet
1887

was recorded on the Texas coast was between 1891 and 1893 (Lowry, 1959).

Droughts may have made the pass more vulnerable to shoaling by hurricanes. During the last week of September 1873, a large hurricane approached the mouth of the Rio Grande and then curved northeast through the middle of the Gulf of Mexico (Sugg and Carrodus, 1969). Waves generated by this hurricane would have traveled westward to produce an increased rate of southwestward littoral drift at Pass Cavallo. Tides probably were up at least 2 feet for several days so that waves were able to build up Pelican Island, prograde the tip of the axial trough adjacent to Matagorda Island. These waves were probably swell, no longer under the influence of hurricane winds. Thus, there would have been no hurricane wind tides in Matagorda Bay that would have enhanced ebb currents to counter shoaling on the Gulf bar.

The smaller cross-section, however, was not a permanent condition. By 1887, Pass Cavallo again had attained a stable entrance area with respect to tidal discharge computed on the area of the bay (Fig. 9). The enlargement might have happened because velocities computed for the 1874 cross-section indicated the potential for erosion. However, several large hurricanes struck the Matagorda Bay area in July 1874, in 1875, 1877 and 1886 (Price, 1956b; Sugg and Carrodus, 1969). These storms completely wiped out the town of Indianola on the west shore of Matagorda Bay with high tides and waves. No doubt the enlargement of Pass Cavallo's cross-section from 1874 was partly due to these storms.

The current velocity computed for Brown Cedar Cut (Table 1) although close to velocities computed for Pass Cavallo, is larger than observed there by Mason and Sorensen in 1971. The largest velocity determined from tidal data during flood or ebb cycles by Mason and Sorensen (1971, p. 66) was about 3.5 feet/second, with most being 2.0 feet/second, or less.

The cross-section used by Mason and Sorensen (1971, Fig. 48) was located inside the inlet near the back side of the barrier islands. It is possible that velocities would be higher through a cross-section located closer to the Gulf with a smaller area. Such a cross-section would be more subject to shoaling by littoral drift and require higher velocities to maintain the channel. Alternately, the area of the cross-section chosen by Mason and Sorensen at Brown Cedar Cut may be in equilibrium with the larger tidal discharges shown in Table 1, whenever they occur. Most shear stresses and velocities measured by Mason and Sorensen (1971, pp. 74-76), were less than critical, so that they may not have observed the events that scoured that part of the channel.

Galveston Entrance had the lowest calculated velocities of all three inlets at any time (Table 1). In 1867, Galveston Entrance (also known as Bolivar Roads) was a natural entrance, and was not jettied or dredged (Fig. 10). Assuming tidal ranges had not changed since 1867 I had estimated the average tidal range in Galveston Bay to be about 1.1 feet from the Tide Tables (U.S. Coast and Geodetic Survey, 1969, p. 240), which may not be representative for Galveston Bay. Unlike Matagorda Bay, which is mainly a large, unsegmented basin with a fairly simple tidal circulation, Galveston Bay is divided by large oyster reefs into several interconnected tidal basins. Tidal ranges are 1.4 feet near Texas City, 1.2 feet at the east end of East Bay, and about 1.0 foot elsewhere. An average tidal range of 1.2 or 1.3 feet throughout the Galveston Bay system would have increased the calculated velocity slightly. Possibly velocities in Galveston Entrance in 1867 were not as high as they are now that the channel is jettied and dredged. Inlets on coasts with dominantly diurnal tides tend to have mean velocities of about .85- .95 m/sec, or about 2.73- 3.05 ft/sec (Brunn, 1966), which is close to the mean velocity of 2.78 ft/sec computed for Galveston (Table 1).

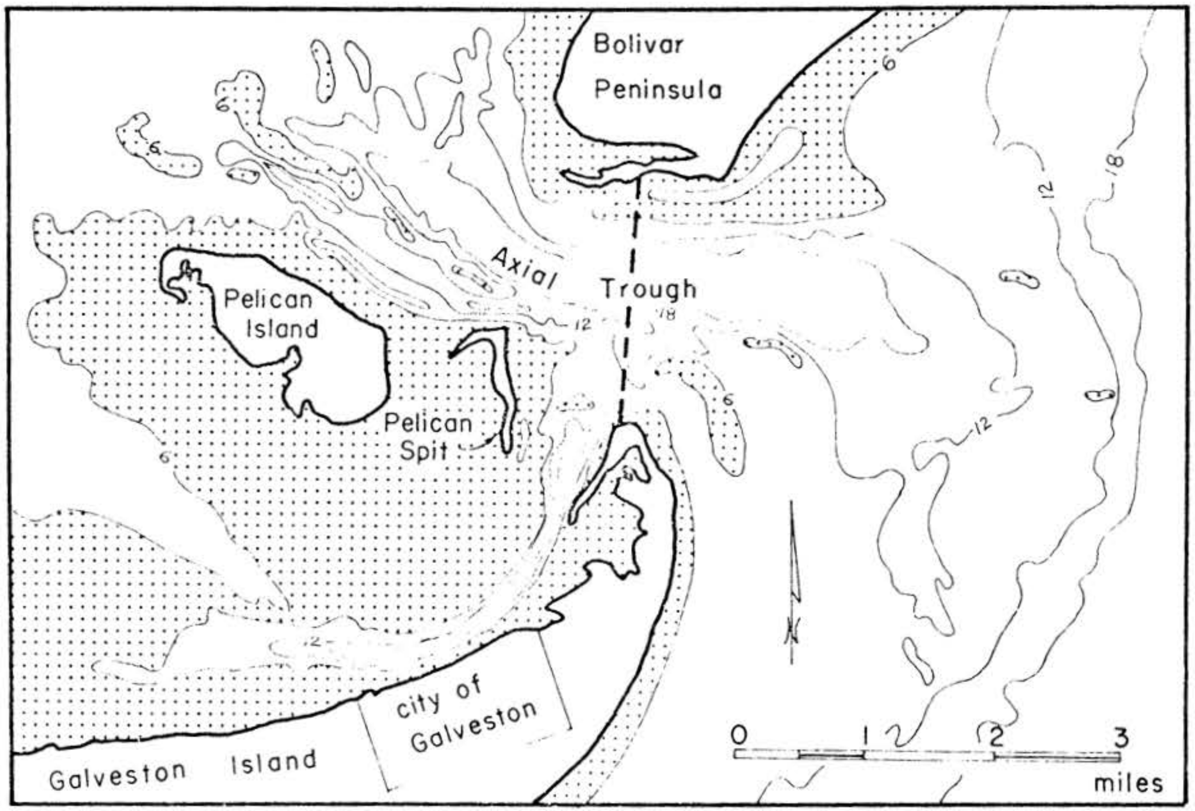


Figure 10. Galveston Entrance, 1867. The entrance area at the cross-section line was about 145,000 square feet.

Possibly the cross-section at Galveston is slightly large with respect to discharge for another reason. The channel that connects the pass to West Bay curves along the back of Galveston Island and enters the axial trough at the cross-section. The interaction of waves and converging currents at that point might enlarge the cross-section without reducing current velocities in the axial trough (Brunn and Gerritsen, 1960, p. 62).

Shape of Entrance Cross-section.--Some inlets maintain a unique cross-sectional shape for decades, some never at all. In general, if littoral drift rate is large relative to tidal discharge the inlet will have an unstable cross-sectional shape. On the other hand, if littoral drift rate is small relative to tidal discharge the cross-sectional shape tends to be stable.

Brunn and Gerritsen (1960, p. 87) use two ratios, $\Omega/2M$ and Q_{max}/M to describe stability of cross-sectional shape, where Q_{max}= tidal discharge at spring tide conditions in cubic feet/sec, Ω = tidal prism in cubic feet at spring tide conditions and M = littoral drift in cubic feet per year (about 5.4 million cu. ft./year) near Pass Cavallo) (Mason and Sorensen, 1971, pp. 110-114). In general, greater shape stability is indicated if $\Omega/2M$ is greater than 300, and if Q_{max}/M is greater than

.01; and less shape stability if $\Omega/2M$ is less than 100 or Q_{max}/M is less than .01. Table 2 gives these ratios for Pass Cavallo, Galveston Entrance and Brown Cedar Cut.

Values for Pass Cavallo and Galveston fall well within Brunn and Gerritsen's values for stable cross-sectional shape. As tidal discharge decreased at Pass Cavallo from 1858 to 1971, both ratios approached unstable values. In 1971 Pass Cavallo probably still had a stable cross-sectional shape--even though the ship channel may have taken about one-half the tidal of Matagorda Bay before 1965 (Appendix C).

Values for Brown Cedar Cut, however, fall well within values for unstable cross-sectional shape. This suggests that shoaling by littoral drift is a continual problem, and that some of the discrepancies that Mason and Sorensen (1971, p. 68-72) found between measured and computed velocities may be due to a temporarily reduced cross-sectional area at the entrance.

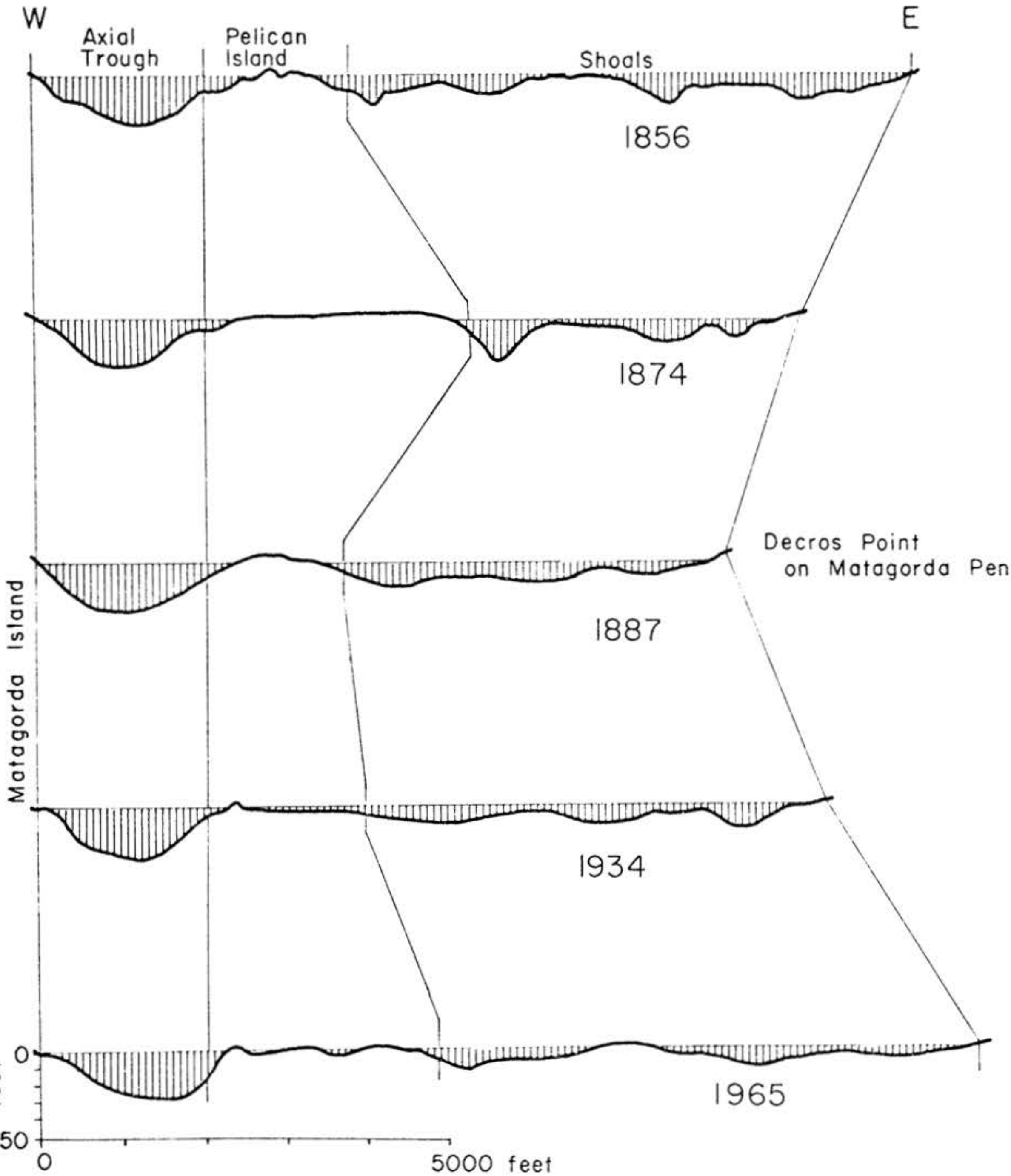
Figure 11 shows five cross-sections for Pass Cavallo between 1856 and about 1965. All cross-sections are located where flood and ebb channels converge near Pelican Island. As is indicated by the Q_{max}/M and $\Omega/2M$ ratios, the shape of the entrance cross-section tends to remain stable even though the area changes. These

Table 2. Stability factors for Cross-sectional Shape.

	$\Omega/2M>300$	$\Omega/2M<100$	$Q_{max}/M>0.01$	$Q_{max}/M<0.01$
Pass Cavallo before 1930	1560		0.069	
1934-1965	1300		0.058	
after 1965	840		0.037	
Galveston Entrance 1867	2250		0.096	
Brown Cedar Cut - 1971		46.0		0.00196

Figure 11.

Entrance cross-sections of Pass Cavallo from 1856 to about 1965. Cross-sections were drawn where flood and ebb channels converge between Matagorda Island on the west and Matagorda Peninsula on the east. Sections are oriented perpendicular to the flow across the axial trough to Pelican Island and from Pelican Island to Matagorda Peninsula. Almost all adjustments in cross-sectional area have occured on the shoals east of Pelican Island.


W
E
Axial Trough
Pelican Island
Shoals
1856
1874
Decros Point on Matagorda Pen.
1887
Matagorda Island
1934
1965
0
feet
50
0
5000 feet

cross-sections are asymmetrical with respect to the axial trough. The deep axial trough is located adjacent to Matagorda Island, while an area of shifting channels and shoald is located between Pelican Island and Matagorda Peninsula. Note that although Pelican Island is always present, its subaerial extent and the width of the shoal it sits on are variable.

The location of Pass Cavallo at the extreme south end of the bay and the offset of Matagorda Island from Matagorda Peninsula apparently contribute to the asymmetry of the cross-section. The almost due north orientation of the axial trough cuts diagonally across the barrier trend. This orientation is apparently the result of the interaction of southwestward littoral drift and enhanced tidal drain action during northers (Price, 1952). The axial trough never has been charted in a more central position in the cross-section so that this position against Matagorda Island is stable. However, currents in the axial trough flow through a longer constricted reach between Matagorda Island and the Gulf bar (about 14,000 feet) than if they flowed directly across the Gulf bar east of Pelican Island (about 4000 feet). That the shorter route is not a preferred location for the axial trough probably is due to the southern location of the inlet relative to Matagorda Bay causing ebb currents to funnel straight south (Fig. 2). In order to take advantage of the shorter route adjacent to Matagorda Peninsula, ebb currents would have to make a 90 degree turn. An extreme bend is less efficient than a longer constricted, but straight channel so that the channel shoals and narrows.

Changes since 1856, in the cross-sectional areas of the axial trough and the shoals east of Pelican Island, are given in Table 3. Before the Colorado River delta reduced the area of Matagorda Bay, the cross-sectional area of Pass Cavallo almost was divided evenly between the axial trough and the shoals (Fig. 7). At that time the shoal area at Pass Cavallo may have carried as much as one-half the tidal flow. However, due to the shallower depths (usually 10 feet or less) and wave action on the bar, this cross-section probably was less efficient for transfer of flow than the axial trough which averaged 30 feet deep. Therefore as discharge decreased, the shoals lost cross-sectional area faster than the axial trough.

At Pass Cavallo and Galveston Entrance about 40 percent of the entrance area were shoals less than 6-12 feet deep. The higher percentages at Pass Cavallo, especially in 1856 and 1887, include some deep channels over the bar east of Pelican Island, so that the actual

Table 3. Cross-sectional areas of the axial trough at Pass Cavallo and the shoals east of Pelican Island since 1856. Galveston Entrance in 1867 is included for comparison. Cross-sections are located where flood and ebb flow converges at Pelican Island.

	Axial trough sq. ft. X 10^4	Shoals sq. ft. X 10^4	Percentage of total cross-section in shoals
Pass Cavallo			
1856	4.54	4.405	49
1874	4.09	2.95	42
1887	4.8	4.0	45.5
1934	4.37	3.26	42.5
1965	4.38	2.77	39
Galveston Entrance			
1867	8.8	5.7	38

percentage of shoals was probably closer to 40 percent. Possibly the shoal area serves to protect the geometry and position of the axial trough by taking up slack in short-term variations in littoral drift rate and direction, and tidal discharge. A smaller percentage of shoals might tend to force migration and shoaling of the axial trough during peak periods of littoral drift.

Channel pattern and the Gulf bar.--The relative magnitudes of littoral drift and tidal discharge at Texas inlets are related to the way littoral drift material in the Gulf is by-passed across the mouth of an inlet and also to the form of both the channel pattern (Brunn and Gerritsen, 1960, p. 84ff), and the Gulf bar. For example, littoral drift material is carried into the inlet by flood currents, and some of that is returned to the downdrift side by ebb currents, at inlets where tidal flow by-passing is dominant. Because tidal discharge is strong relative to littoral drift rate, tidal flow by-passing at Texas inlets usually is associated with a Gulf bar that bulges 1-3 miles away from shore into water 10-12 feet deep and with well-developed flood and ebb channels separated by shoals (Fig. 10). Conversely, most littoral drift material is by-passed over the Gulf bar at Texas inlets where bar by-passing is dominant. At these inlets, because the volume of flow is small relative to littoral drift rate, inlet channels usually do not exhibit distinct flood and ebb characteristics, and the bar is shallow, less than 6 feet deep and fairly close to shore (less than 1 mile).

The interaction of tidal flow and littoral drift is shown in the ratio, M/Q_{max}. Brunn and Gerritsen (1960, p. 84) found that values of M/Q_{max} greater than 200-300 indicated dominantly bar by-passing, and M/Q_{max} less than 10-20 indicated dominantly tidal flow by-passing. Table 4 shows these ratios for Pass Cavallo, Galveston Entrance and Brown Cedar Cut. Before 1965, Pass Cavallo had values for M/Q_{max} that indicated dominantly tidal flow by-passing. But after 1965, the ratio indicated mixed bar and tidal flow by-passing. By comparison, Galveston Entrance in 1867 was definitely a tidal flow by-passing inlet. Most of its Gulf bar was deeper than 9-11 feet, and extended about 3 miles offshore (Fig. 10). In contrast, Brown Cedar Cut, was a dominantly bar by-passing inlet. At Brown Cedar Cut the surf zone (less than 4-6 feet deep) was almost continuous across the mouth of the inlet and the Gulf bar bulged seaward only slightly (Mason and Sorensen, 1971, Fig. 22, p. 48).

Where tidal flow by-passing is dominant, three types of channels can be distinguished: flood channels that mostly carry flow into a tidal basin, ebb channels

Table 4. Stability factors for material transfer across the mouth of Pass Cavallo, Galveston Entrance and Brown Cedar Cut.

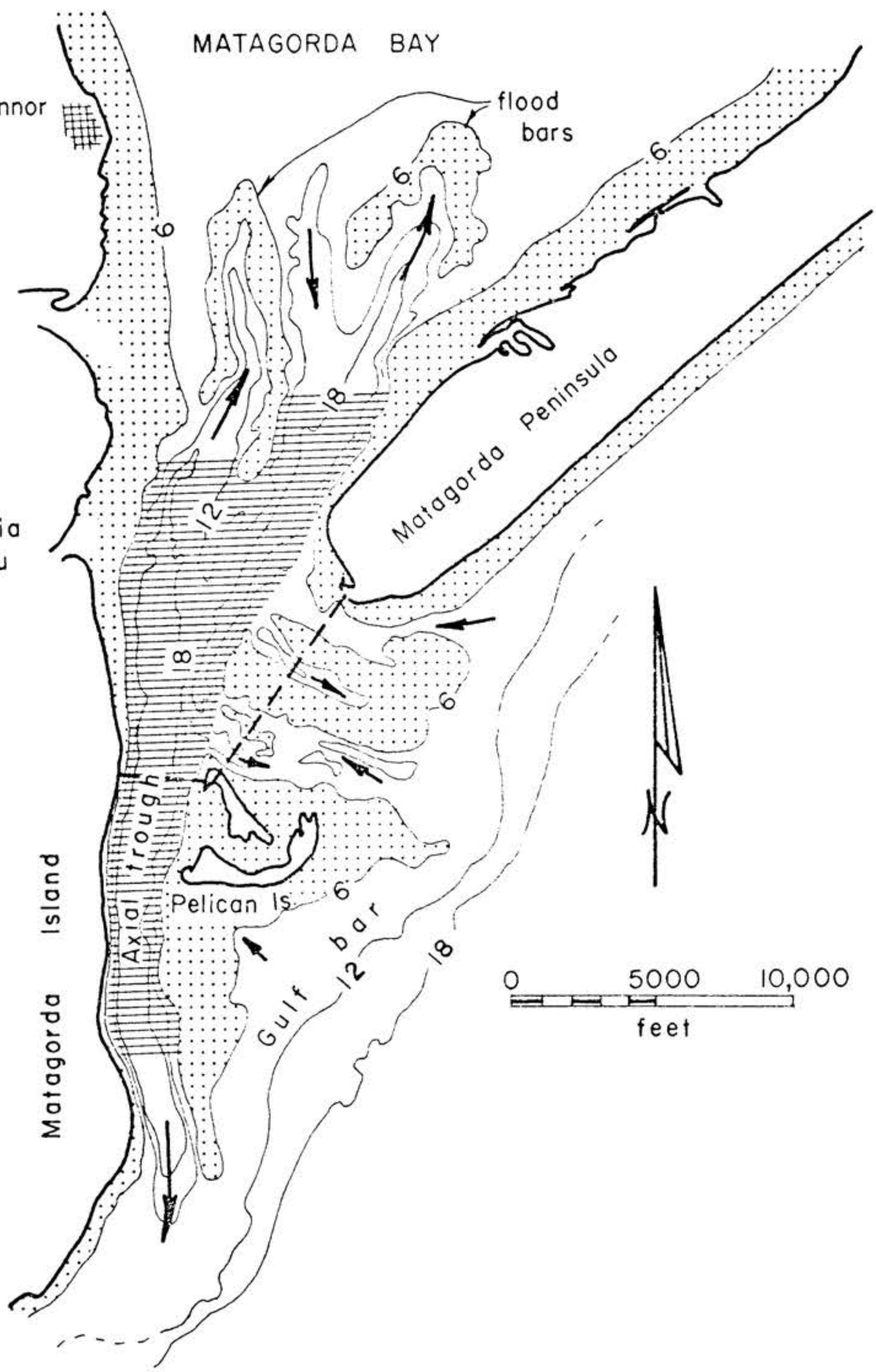
	$M/Q_{max}<10-20$ TIDAL FLOW BY-PASSING	MIXED	$M/Q_{max}>200-300$ BAR BY-PASSING
Pass Cavallo before 1930	14.4		
1934-1965	17.2		
after 1965		27.0	
Galveston Entrance-1867	10.4		
Brown Cedar Cut - 1971			510

that mostly carry flow out of a tidal basin, and neutral channels that carry both flood and ebb flow (Brunn and Gerritsen, 1960, p. 10; Van Veen, 1950; and Price, 1963). Figure 12 shows flood, ebb and neutral channels at Pass Cavallo in 1856. For Pass Cavallo, even though the channel pattern has changed somewhat with each decrease in discharge, the general arrangement of channels has persisted since 1856.

In Pass Cavallo since 1856 all tidal flow has passed through neutral channels, between the barrier islands, especially the axial trough, and distinct flood and ebb channels occur only where the flow enters or issues from the inlet. In Matagorda Bay very small, acruate depositional bars (flood bars) have been located at the ends of flood channels, but ebb channels, that are scoured into the bay bottom by entering ebb flow, have not had bars (Fig. 12). On the Gulf bar, the ends of ebb channels were recognized by arcuate bars or seaward bulges in the surf zone, while flood channels were broad, relative to ebb channels, and usually deep enough to separate the line of breakers in depths less than 6 feet (Fig. 12). Shoals or bars have separated neutral channels from neutral channels, and flood channels from ebb channels, especially on the Gulf bar (Fig. 12). Brunn and Gerritsen (1960, p. 10) note that flood channels tend

Figure 12

Channel pattern and Gulf bar at Pass Cavallo, 1856. The entrance cross-section at the profile line was 89,450 square feet. The pattern indicates neutral channels. Arrows pointing towards Matagorda Bay represent flood channels and arrows pointing towards the Gulf, ebb channels.

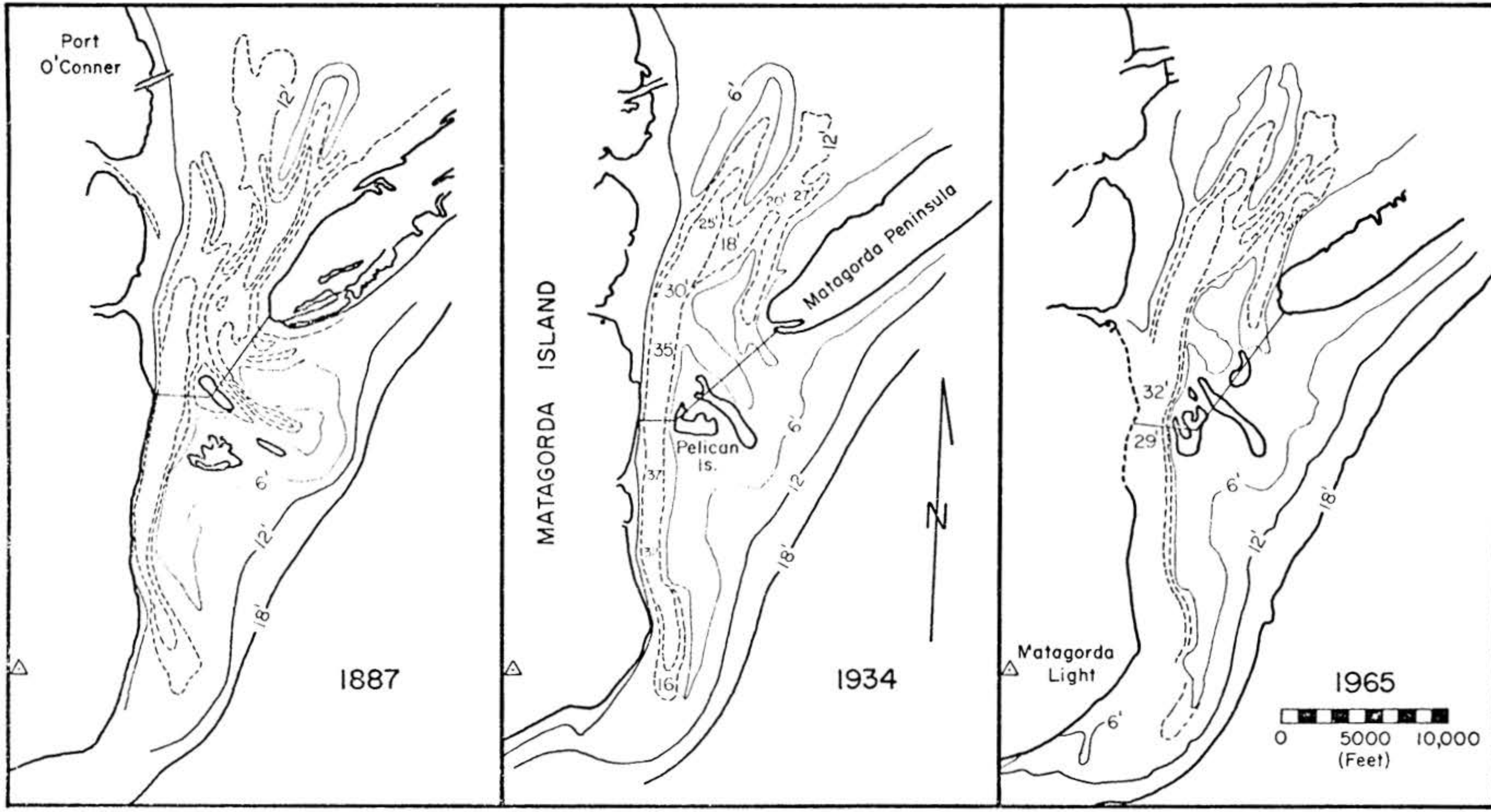

MATAGORDA BAY
Port O'Connor
flood bars
Big Bayou
Saluria Bayou
Matagorda Peninsula
Axial trough
Pelican Is
Gulf bar
Matagorda Island
6
12
18
8
0
5000
10,000
feet
N

to dominate on the bay side and ebb channels on the sea side, probably because issuing currents develop prominent depositional bars and deep channels.

Before 1930, and especially in 1887, Pass Cavallo was almost a double inlet with nearly separate channel systems on either side of Pelican Island (Fig. 12 and 13). The axial trough outlined by the 18 foot contour was an almost straight neutral channel, about 30 feet deep, that was bordered on the east side by the Gulf bar and on the west by Matagorda Island. Arcuate bars were located at opposite ends of the axial trough. Just bayward of Pelican Island the axial trough appeared to branch, but was separated from the neutral branch channel by a small shoal. The tendency for shoals to separate these neutral channels possibly indicates that, for part of each tidal cycle, flood and ebb currents are out of phase in each channel. The neutral channel ran NE along the back side of the Gulf bar. Most of the flood flow entering the pass over the Gulf bar probably discharged over the flood bar at the bay end of this channel. A single ebb channel enters this branch channel at an angle of about 20 degrees, and apparently carried the most concentrated part of the ebb flow. The rest of the ebb flow entered the pass on the other sides of the flood bars.

Figure 13

Pass Cavallo in 1887, 1934 and about 1965. Between 1887 and 1934, the entrance area at the cross-section line decreased from 88,000 square feet to 76,300 square feet to 71,500 square feet. Other changes include a change from 2 flood bars to one, and shoaling on the gulf bar.


Port O'Conner
12'
6'
12'
18'
1887
MATAGORDA ISLAND
6'
12'
25'
20'
27'
18'
30'
Matagorda Peninsula
35'
Pelican Is.
37'
6'
12'
18'
16'
N
1934
32'
29'
6'
12'
18'
Matagorda Light
6'
1965
0
5000
10,000
(Feet)

By 1934 (Fig. 13) the axial trough had straightened slightly by moving closer to Matagorda Island north of Pelican Island. And the deep, neutral branch channel had disappeared. Only one flood bar was present in Matagorda Bay and that at the end of the axial trough. Flood and ebb channels on the bar east of Pelican Island were shallower and less distinct. An apparent flood channel, 6-12 feet deep, intersected the axial trough north of Pelican Island in 1934 (Fig. 13), but by 1965 this channel was closed by a subaerial bar similar to Pelican Island (Fig. 13). The absence of this second flood bar and deep neutral channel suggests that most of the ebb and flood flow was now confined to the longer axial trough.

A remnant of the double nature of the inlet still existed in 1934 and 1965 in the small neutral channel adjacent to the back side of Matagorda Peninsula (Fig.13). However, due to its size this channel apparently carried only a small part of the tidal discharge. On the 1971 NASA photographs (frontispiece) the channel pattern was similar to that in 1965, except that this small neutral channel was shorter and no longer connected to the ebb channel that entered the axial trough. On the 1971 photographs this neutral channel was located entirely on top of shoals extending bayward from the Gulf bar, so that shoaling in Matagorda Bay from the Gulf bar appeared more extensive.

The Gulf bar at Pass Cavallo has had two distinct features that have persisted since 1856. First its overall shape has been stretched out by the asymmetry of the axial trough and shoals, and by the extreme offset of Matagorda Island from Matagorda Peninsula so that it is not as arcuate nor does it bulge as far Gulfward as the bar at Galveston Entrance (Fig. 10). And secondly, the relative location of Pelican Island on the bar has not changed even though the shape and size of Pelican Island has been different on every chart (Fig. 12 and 13).

Apparently Pelican Island is a natural divide for inlet currents, some of which flow straight down the axial trough and some of which take the shorter route to the Gulf east of Pelican Island. The island itself seems to be built above mean low water by the interaction of waves and currents during very high storm tide. In March 1971, Pelican Island was about 3 feet above MLW (Fig. 14). At that time large shells and driftwood were abundant on the surface and a steep storm beach with several shell and debris lines occurred along the Gulf margin. The island margin adjacent to the axial trough seemed to be eroding and the offshore slope there was very steep.

Figure 14

Photographs of Pelican Island in March 17, 1972 at morning low tide.

A. East shoreline of Pelican Island looking south towards Gulf of Mexico. Rippled blowouts due to strong SE wind some days earlier.

B. West shoreline of Pelican Island adjacent to axial trough looking north towards Matagorda Bay. Note the steep cut bank probably eroded by currents at higher water stage.

A

B

Figure 14

Before 1930, the Gulf bar bulged seaward at the 12-foot contour on either side of Pelican Island opposite channels deeper than 9-12 feet. Most of the top of the Gulf bar, however, was shallower than 6 feet. Lines of breakers usually curved around the Gulf side of Pelican Island and occurred on shoals separating flood and ebb channels, but depths less than 6 feet were not continuous with the surf zone on Matagorda Peninsula or Matagorda Island. Also before 1930, the bay margin of the Gulf bar was bordered by the axial trough and the neutral branch channel. These channels prevented shoaling in Matagorda Bay from the Gulf bar--even in 1874 when the entrance cross-section apparently was choked with littoral drift material (Fig. 9).

In 1934, with the reduction in area of Matagorda Bay by the Colorado River delta, the Gulf bar made these changes (Fig. 13): The area between Pelican Island and Matagorda Peninsula shoaled so that the axial trough was the only channel with passage of about 9-12 feet over the bar table (Table 3). The zone of breakers and depths less than 6 feet now extended unbroken from Matagorda Peninsula to the axial trough. The bar bulged bayward between Pelican Island and Matagorda Peninsula due to the shoaling of the deep bay channel that had been located adjacent to the bar. And the map profile at the 12-foot contour was smooth except where it bulged slightly more seaward opposite the axial trough. Probably the M/Q_{max} ratio of 17.2 indicates that the pass was barely in a tidal flow transfer state (Table 4). Only the axial trough seemed to be capable to by-passing sand by tidal flow action, and most of the material was moved by littoral drift across the bar.

Sometime between 1934 and 1952, a small inlet known as Green's Bayou was opened about 11 miles north of Pass Cavallo, probably by a hurricane. There was no inlet at this site in 1934 but numerous washover channels indicate that small inlets may have occurred in the past (Coast Chart 1284, 1939 ed.). By early 1953 when some USDA photographs were taken of this part of the coastline, Green's Bayou was only slightly larger than Brown Cedar Cut, which had been opened about 1930 by a hurricane (Mason and Sorensen, 1971, p. 25). In fact, the channel pattern and tidal deltas of these two inlets look nearly identical (Fig. 15). Apparently the tidal discharge through Green's Bayou was small. By 1953 the inlet was about 660 feet wide and may have averaged about 6 feet deep. For an entrance area of about 4000 sq. feet during spring tides (V_{max} = 4.2 ft./sec.), discharge would be about 16,500 cu. ft./sec. This is only slightly larger than that computed for Brown Cedar Cut in 1971

Figure 15

Aerial photographs of Brown Cedar Cut and Green's Bayou, two small inlets through Matagorda Peninsula. The location of these inlets is shown on figure 2.

Copied from U. S. Dept. of Agriculture, photo-index sheets, 1952.

Brown Cedar Cut

Green's Bayou

Figure 15

(Appendix C). The effect of this small inlet on Pass Cavallo was seen mostly on the Gulf bar. The 1952 edition of USGS topographic maps of the Pass Cavallo area show a shallow bar encroaching on the axial trough from Matagorda Island, and a second subaerial bar similar to Pelican Island developed on the Gulf bar halfway between Pelican Island and Matagorda Peninsula. This is the first time that a subaerial bar was located on the Gulf bar away from the site of Pelican Island and indicates that more shoaling had occurred on the Gulf bar.

The Matagorda Ship Channel was dredged to a depth of 29 feet for a width of 300 feet in October of 1965, although the channel was still under construction (Coast Chart 1284, 1965 ed.). When completed the ship channel was about 1000 feet wide, with depths of about 20-30 feet on the sides and 38 feet deep in the middle width of 300 feet (Coast Chart 889-SC, Oct. 1970). Because some of Matagorda Bay's tidal prism now passed through the dredged channel, shoaling was noted over the Gulf bar on either side of the axial trough (Fig. 13). By 1971 with the completion of the Matagorda Ship Channel, shoaling into Matagorda Bay was more extensive, and several emergent bars developed on the Gulf bar east of Pelican Island (Coast Chart 1284, Jan. 1972 ed.). Also, the axial trough and Gulf bar adjacent to Matagorda Island did not extend as far Gulfward. On the 1971 photograph (frontispiece) the surf zone was nearly continuous from Matagorda Island to Matagorda Peninsula, indicating water depths of about 6 feet across most of the Gulf bar. There are no wind waves in Matagorda Bay or abnormal tide levels on the flood delta to suggest a different interpretation of the 1971 photograph.

In summary, the range of M/Q_{max} values for tidal flow by-passing defined by Brunn and Gerritsen (1960) seem to apply to changing conditions at Pass Cavallo (Table 4). As discharge has decreased (Table 1) less littoral drift material was by-passed by tidal flow action and more by bar by-passing. Before 1930, littoral drift material was stored only in the two flood bars in Matagorda Bay (Fig. 13). This indicates that tidal flow by-passing was relatively efficient. The most pronounced changes in geometry of the Gulf bar and in the channel pattern occurred after 1930 when the axial trough lengthened and straightened to accomodate some of the flow that had been carried by the second neutral channel. The strong bulge of the Gulf bar, and the small flood bar opposite the axial trough in 1934 indicates that the axial trough, at least, was still fairly efficient in by-passing littoral drift material (Fig. 13). Further reductions in discharge did not strongly affect the channel pattern except to shorten some of the channels. After 1965, the reduced tidal discharge at Pass Cavallo was indicated by a less pronounced bulge of the Gulf bar opposite the axial trough, and also by depths less than 4-6 feet that were continuous from Matagorda Peninsula to Matagorda Island--except for a narrow channel at the axial trough. In 1971, M/Q_{max} of 27.0 indicated that neither tidal flow by-passing nor bar by-passing were dominant. At that time more littoral drift material had been deposited in Matagorda Bay opposite the axial trough and the Gulf bar than previously.

Channel length.--Shoaling at inlets is usually the result of continuous prolongation of the inlet channels without an accompanying increase in discharge (Brunn and Gerritsen, 1960, p. 8). Where large deposits accumulate in the bay around flood and ebb channels or where only the inlet mouth migrates, prolongation and shoaling occur because friction in the longer channel reduces tidal discharge and entrance area. However, at Pass Cavallo the inlet mouth does not seem to migrate significantly and bay deposits are not abundant opposite flood channels in Matagorda Bay, especially prior to 1965. Channel lengths were measured at Pass Cavallo to see if reductions in tidal discharge resulted in a corresponding change in these channels. I measured channel lengths to the nearest

100 feet from where they began to be incised into the bay bottom. At Pass Cavallo, incised channels included all channels deeper than the 12-foot depth contour.

The total length of incised channels decreased with each permanent decrease in tidal discharge at Pass Cavallo. Total channel length was about 69,000 feet in 1856, 62,000 feet in 1934, 60,000 feet in 1965 and about 43,000 feet in 1971. An exception to this trend occurred in 1887 when total channel length was about 77,000 feet. The greater channel length in 1887 than in 1856 was due to a longer issuing ebb channel over the Gulf bar east of Pelican Island and to a longer entering ebb channel in Matagorda Bay (Fig. 13). These prominent ebb features at Pass Cavallo in July of 1887 probably were left over from the August 1886 hurricane that produced high tides in Matagorda Bay and completed the destruction of Indianola (Price, 1956b; Sugg and Carrodus, 1969). Apparently channel lengths in the bay respond less quickly to reductions in tidal discharge than the cross-sectional area. At the time of the 1887 survey, the cross-section appeared to be in equilibrium with the tidal discharge, whereas the total channel length and channel pattern still may have showed effects of higher hurricane discharges.

The relationship of discharge at spring tide conditions (Q_{max}) to total channel length (Lt) is given in

Table 5. For Pass Cavallo and Galveston Entrance, Qmax/Lt tends to fall between 5 and 6 ft^2/sec, suggesting that there might be an optimum channel length for a given todal discharge. The optimum channel length would be the distance over which a particular tidal discharge can erode and transport its bed materials. Because both channel legnth measurements and computed tidal discharge are at best estimates, stable values of Qmax/Lt probably could vary between 4 and 7 ft^2sec. on the Texas coast. If for any reason channel length exceeds this distance at an inlet, such as at Brown Cedar Cut, the channel tends to shoal. Application of channel length measurements to the origin of some surge channels and other flood delta channel systems on the central Texas coast is discussed in Appendix D.

Geographic Stability

Most tidal inlets migrate in the direction of dominant littoral drift so that no inlet is perfectly stable with respect to geographic location. Apparently the rate at which an inlet migrates and therefore its relative stability is related to the magnitudes of littoal drift and inlet currents (Brunn and Gerritsen, 1960, p. 7) and also to changes in geometric stability.

Table 5. Relationship of discharge at spring tides (Qmax) to channel lengths (Lt) at Pass Cavallo, Galveston Entrance and Brown Cedar Cut.

	Qmax/Lt (ft^2/sec)
Pass Cavallo	
1856	5.45
1887	4.87
1934	5.06
1965	5.26
1971	5.11
Galveston Entrance	
1867	6.0
Brown Cedar Cut	
1971	1.77

Often, reduction in discharge and entrance area is accompanied by a temporarily increased rate of migration. On the Texas coast, tidal inlets tend to be geographically stable (Price, 1952), that is, large Texas inlets have been at about the same location since the 17th or 18th centuries. At some Texas inlets, for example, Aransas Pass, and Cedar Bayou, rapid shifting of inlet channels has occurred mostly at the Gulf mouth, while behind the barriers channels have tended not to move (Price, 1959; Simmons and Hoese, 1959; R. Nordquist, 1972, personal communication). The result of such partial migration is prolongation of the channel length and eventually shoaling and even closure. Usually partial migration of the inlet mouth occurs over a well-defined zone so that hurricanes periodically relocate the channel in a shorter course (Brown, 1928, p. 520; Price, 1959; Simmons and Hoese, 1959). Pass Cavallo, however, apparently has migrated relatively slowly as a unit.

Migration of the axial trough and shoreline changes at Pass Cavallo since 1856.--True inlet migration occurs when the axial trough moves. Shoreline changes sometimes are used to describe inlet migration, but over a short interval of a few decades are not as sensitive as measurements of the axial trough.

Discrepancies in scale or in location and shape of geographic features existed on all editions of coast charts of the Pass Cavallo area. To minimize these discrepancies, I reduced charts at different scales to a scale of 1:80,000, used on some U.S. Coast and Geodetic Survey charts. Two maps at a time when overlain on a light table and changes were measured to the nearest 100 feet. Table 6 gives changes in position of the axial trough and shorelines at Pass Cavallo since 1856. The locations where changes in shorelines and axial trough were measured are shown in Plate 1.

Changes in position of the axial trough did not occur everywhere at the same time or rate (Table 6). Usually either the northern part of the axial trough (profiles III, IV), or the southern part (profiles V, VI) migrated westward, while the opposite part remained stationary or migrated in the opposite direction. The net migration of the axial trough between 1856 and 1971 (115 years) was about 1500 feet west opposite profile III, about 800 feet west opposite profiles IV and V, and no net change opposite profile VI.

Accurate shoreline surveys along the low-lying western edge of the pass were first made about 1860, and revised in 1887 (Coast Chart 209, 1918 ed.). Between 1887 and 1971 (84 years), shorelines along the western

Table 6. Migration of the axial trough at Pass Cavallo and shoreline changes 1856-1971. AT = axial trough migrations in feet. S = shoreline changes in feet. N,S,E,W refer to compass directions in which shoreline moved.

Dates		Profile locations, Matagorda Island and flood delta I	II	III	IV	V	VI	Matagorda Peninsula BAY	GULF	DECROS PT.
1856-1887	AT	-----	-----	1000W	0	0	0	-----	-----	-----
	S	-----	-----	-----	----	----	----	-----	-----	-----
1887-1934	AT	-----	-----	500W	500W	0	800E	-----	-----	-----
	S	0	0	200W	1500W	500W	200E	1000S	200N	0
1934-1965	AT	-----	-----	0	0	800W	300W	-----	-----	-----
	S	500W	200W	500W	300E	800W	300W	0	800N	500E
1965-1971	AT	-----	-----	-----	300W	----	500W	-----	-----	-----
	S	0	300W	200E	100W	200W	700W	0	300S	2000W
TOTAL	AT 115 yrs.	-----	-----	1500W+	800W	800W+	0			
	S 84 yrs.	500W+	500W+	500W	1300W	1500W	800W	1000S	700N	1500W

W = movement of shoreline or axial trough westward
E = movement of shoreline or axial trough eastward
N = movement of shoreline or axial trough northward
S = movement of shoreline or axial trough southward

Accurate shoreline surveys along the low-lying western edge of the pass were first made about 1860, and revised in 1887 (Coast Chart 209, 1918 ed.). Between 1887 and 1971 (84 years), shorelines along the western margin of Pass Cavallo eroded between 500 and 1500 feet westward, while the tip of Matagorda Peninsula prograded about 1500 feet westward (Table 6). The greatest net shoreline changes occurred opposite Pelican Island (profiles IV, V) and at the tip of Matagorda Peninsula (Decros Point). During the same 84 years, Pass Cavallo's axial trough had migrated between 500 and 800 feet westward. Generally shorelines along the western margin of Pass Cavallo migrated in the same direction as the axial trough. At profiles IV and V, the shoreline eroded almost twice as far as the axial trough migrated. This caused the width of gently sloping shoal between the axial trough and western inlet shoreline to increase from less than 300 feet to almost 1000 feet between profiles IV and V (Plate 1). About 700 feet more shoreline erosion than axial trough migration is insignificant to the shape stability of the entrance cross-section (Fig. 11), especially as the width between the barriers is almost 2 miles.

One possible explanation for erosion of shorelines north of profile V, in excess of axial trough migration, might be disruption of sediment transport along the sandy inlet-margin shoal from the north and from the south. Smooth, inlet-margin shorelines surveyed about 1860, and also a spit that recurved southward at Big Bayou in 1873 indicate that sandy beaches may have occurred all along the inlet-margin of the flood delta before 1900. Jetties were built partly across the inlet-margin shoal near Port O'Connor about 1918 and longer jetties (to the 6-foot depth contour) about 1940 when the Intracoastal Waterway was constructed (Fig. 13 and Plate 1). After 1918, shorelines north of profile V became progressively more uneven, with shoreline erosion accelerating at profiles I, II, and III between 1934 and 1965 (Table 6). The topographic survey of 1860 showed a continuous line of mounds from Matagorda Island to Saluria Bayou that may have been partly removed by the hurricanes between 1875 and 1886. Sand moving north would be interrupted at the surge channels, Fish Pond and Mule Slough, before reaching Saluria Bayou to produce 1000 feet more shoreline erosion than axial trough migration between 1887 and 1934 (Table 6). A long interval between storms probably heals these surge channels to allow more sand to move north. Between 1934 and 1965 the shoreline at Saluria Bayou temporarily accreted about 300 feet east probably due to this phenomenon.

The difference between change in position of shorelines and of the axial trough is significant when estimating long-term migration rates at Pass Cavallo. Between profiles IV and V the axial trough at Pass Cavallo has migrated about 800 feet over the past 115 years. Shorelines between profiles IV and V, however, have "migrated" 1500 feet westward in 84 years, or about 1785 feet/100 years. Discrepancies between the distance that shorelines and axial trough migrated at Pass Cavallo probably would average out over several centuries, especially before 1918. Thus, a long-term rate of channel and shoreline migration at Pass Cavallo, before jetties were built near Port O'Connor, probably was about 1000 feet/100 years.

Most axial trough migration at Pass Cavallo seems to have occurred in pulses related to closely spaced events such as northers and hurricanes, and also to permanent reductions in tidal discharge. These events temporarily disrupt equilibrium between tidal discharge, inlet currents and littoral drift. For example, the axial trough opposite profile III migrated about 1000 feet westward between 1856 and 1887 (Table 6, Fig. 12 and 13). This movement was due to an additional ebb channel, probably cut by the hurricanes that destroyed Indianola on Matagorda Bay between 1874 and 1886. By 1918 this channel was "abandoned" and may have shoaled (Coast Chart 209, 1918 ed.). Between 1887 and 1934, westward migration occurred north of Pelican Island (and profile V), and eastward to the south. Most of this change may have been due to the major change in channel pattern that probably occurred rapidly with the reduction in tidal discharge between 1929-1934. Another interval of rapid migration of the axial trough occurred between 1965 and 1971 when tidal discharge decreased after the Matagorda Ship Channel was opened.

Migration keyed to northers and hurricanes would explain why changes have not occurred at the same rate in different time intervals along the axial trough and adjacent shorelines (Table 6). Continued migration of Pass Cavallo southwestward is related to the probability that when disruptions of equilibrium conditions occur the direction of littoral drift at that time will be southwestward. Not only does the annual wind pattern indicate that the dominate direction of littoral drift is southwestward (U. S. Dept. of Commerce, 1966-1970), but strong southwestward drift precedes some northers (Andrews, 1967, personal communication) and also with easterly and southeasterly hurricane winds.

Shoreline changes along Matagorda Peninsula have not been as related to movements of the axial trough as shorelines on Matagorda Island. Little erosion has occurred on the bay shore of Matagorda Peninsula except between 1887 and 1934, when almost 1000 feet was eroded at the double notch about 2 miles east of Decros Point (Plate I). By 1934 instead of two flood bars in Matagorda Bay there was one opposite the axial trough. The second flood bar that had been adjacent to Matagorda Peninsula no longer protected the lower part of Matagorda Peninsula from erosion by north and northeast waves during northers.

Some of the erosion on the Gulf shoreline of Matagorda Peninsula may be related to engineering efforts to divert the mouth of the Brazos River near Freeport about 1930 (Table 6). Erosion at Brown Cedar Cut on the northeastern part of Matagorda Peninsula following this event was noticed by Mason and Sorensen (1971). At Pass Cavallo, however, disappearance of the seaward bulge in the Gulf bar adjacent to Matagorda Peninsula by 1934 might also have caused erosion near Decros Point as southerly waves no longer would be reflected over the bulge (Fig. 13).

Before 1965 erosion or progradation of the Gulf shoreline on Matagorda Peninsula corresponded to erosion or progradation of Decros Point (Table 6). After 1965 Decros Point quickly prograded almost 2000 feet though before it had either eroded or not changed. Probably reduced tidal discharge after 1965 necessitated a smaller entrance cross-section and more shoaling on the Gulf bar near and at Decros Point.

Evidence for migration of Pass Cavallo before 1856.—Pass Cavallo is essentially in the same location since Minet's sketch map in the latter half of the 17th century (Fig. 16). If the charting is basically accurate of the pass area with respect to shoreline trends, then the axial trough at Pass Cavallo may have been 2000-4000 feet to the east of its 1971 location. This also indicates a migration rate during the last 3 centuries of about 1000 feet/100 years. About 3000 feet of migration in 300 years is substantial, but relatively slow because the Pass itself is large. The width between the barriers is about 10,000 feet.

On Matagorda Peninsula adjacent to Pass Cavallo, the pattern of dune ridges indicates that Pass Cavallo had migrated at least 5 miles along Matagorda Peninsula to its present site. Apparently migration of Pass Cavallo began after Matagorda Island was well established. Older dune ridges on Matagorda Island are cut diagonally by a disconformity that would join with about the present trend of Matagorda Peninsula (B. H. Wilkinson, 1971, personal communication). A younger series of dune ridges on

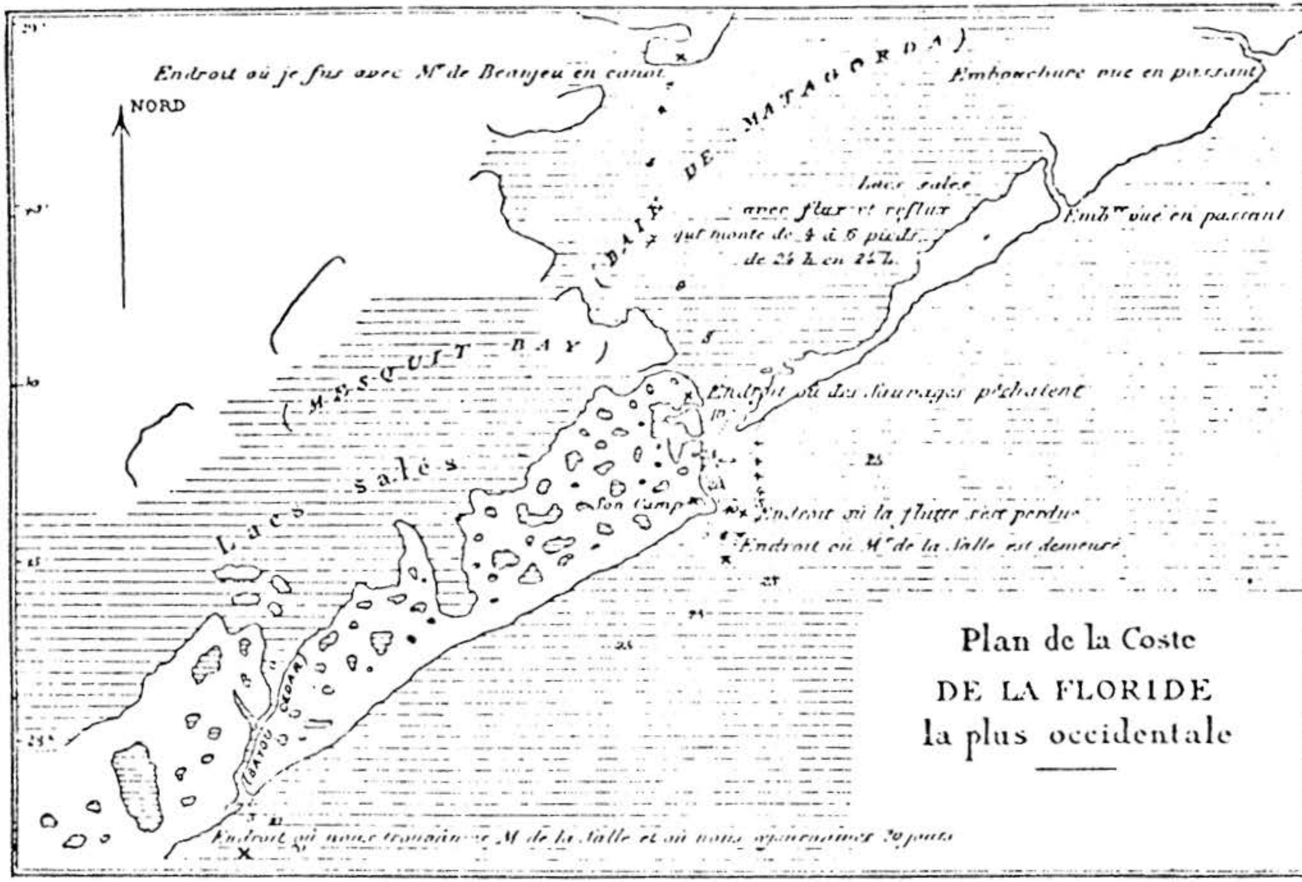


Figure 16. Sketch map of the Pass Cavallo area drawn by Minet. Reference to La Salle suggests that the map was made after 1670. (from a map published in Newport News, Virginia and now stored in the Barker History Center at the Univ. of Texas)

Matagorda Island radiate seaward from this diagonal disconformity. Each successive dune ridge terminates southwestward in a neutral point, or fulcrum (Johnson, 1919, p. 295) that separated the prograding beach near Pass Cavallo from the eroding or stable beach southwest from Pass Cavallo. These younger dune ridges probably formed as the inlet migrated westward.

McGowen (1972, personal communication) suggests that Matagorda Peninsula is much younger than Matagorda Island. Thus, Pass Cavallo may have originated after Matagorda Peninsula grew towards Matagorda Island, the tip of which may have been located 3-4 miles NE. There are two alternate explanations to account for the diagonal disconformity of Matagorda Island's dune ridges. Matagorda Peninsula and Matagorda Island could have retreated after Pass Cavallo was formed. However, erosion of Matagorda Peninsula probably occurred continuously while the peninsula was growing southwest, so that the southwest tip may not have been much farther seaward than the present barrier when the pass began migrating. Thus, the erosion of Matagorda Island to form the diagonal disconformity probably occurred as the downdrift barrier beach trend stabilized with the trend of Matagorda Peninsula when Pass Cavallo first formed.

Assuming a steady migration rate of about 1000 feet/100 years, based on migration of the axial trough since 1856, Pass Cavallo would have been about 5 miles farther east 2600 years ago. Possibly Pass Cavallo began to migrate, and may have formed, about 2600 years ago. The nucleus of Matagorda Island is older still. This coincides with initiation of Texas barrier formation between 5000 and 3000 years ago when the post-Pleistocene sea level rise slowed and apparently stopped (LeBlanc and Hodgson, 1959; Gould and McFarlan, 1959).

THE FLOOD DELTA

Geologists generally use the formal term, tidal delta, to mean an accumulation of littoral drift material that was transported and deposited by inlet currents (Johnson, 1919; Lucke, 1934a and b). Engineers, on the other hand, informally call deposits associated with inlet channels, "bars and shoals" (Brown, 1928; Brunn and Gerritsen, 1960). The implication is that astronomical tidal currents through inlet channels are responsible for tidal deltas as well as bars and shoals. At Pass Cavallo, the only deposits (or tidal delta) associated with the channel pattern, and therefore with inlet currents are the flood bars in Matagorda Bay and the Gulf bar (Fig. 13). I have chosen to call these deposits bars, instead of deltas, because they are not permanent features that will be preserved in a barrier island or bay-lagoon environment. Changes in discharge and channel pattern altered the shape and location of flood and Gulf bars at Pass Cavallo between 1887 and 1934 (Fig. 13). Also, there are no residual flood bars or Gulf bars along the 5-mile segment of Matagorda Peninsula over which Pass Cavallo probably migrated.

Waves in the Gulf and in Matagorda Bay have removed all evidence of these deposits.

In this study, the large, relatively permanent group of salt marsh islands, tidal channels, and storm tidal flats separating Pass Cavallo from Espiritu Santo Bay and also distinct from the inlet channel system, is informally called the "flood delta," rather than tidal delta as had Price (1952) and Andrews (1966, 1970). I believe the term, flood delta, is more appropriate at Pass Cavallo because storm surge or flood features dominate adjacent to the inlet, and the flood delta platform is lobate into Espiritu Santo Bay opposite surge channels and large tidal channels. Apparently, normal (astronomical) tidal currents are unimportant to the genesis of this feature relative to currents and waves generated during higher storm tides. Tide curves at Saluria Bayou and in Espiritu Santo Bay indicate that tidal exchange through Saluria Bayou at all times is slow and out of phase with tidal exchange through Pass Cavallo (Fig. 5 and 6). The predominance of storm flood features indicates that storm surge or flood, mostly from the Gulf of Mexico, generally is stronger than ebb. This is probably because Espiritu Santo Bay is small so that the volume of water accumulated from a storm and thus the ebb discharge would be small. Also, during extreme hurricane tides, some high water in Espiritu Santo Bay may disperse southwest towards other bays and inlets reducing ebb flow to Pass Cavallo (Fig. 1).

I mapped the physiographic features of the flood delta on 1957 Tobin aerial photographs in the fall of 1971. Mapping was field checked in December 1971 and March 1972. Although the photographs and mapping were about 15 years out of date, most physiographic features and depositional environments have changed little except for shorelines (Plate I, and Table 6). In general, I have mapped the flood delta with a definite genetic bias: that the flood delta is a hurricane surge deposit modified by storm waves, and also by tidal currents and marsh growth between storms. This is not to say that the flood delta is totally unrelated to Pass Cavallo. The inlet maintains the opening through which hurricane surge reaches the flood delta, and the inlet contributes sediment to inlet-margin beaches and shoals. And ultimately, the position of the inlet relative to Matagorda Bay and Espiritu Santo Bay has influenced the location and geometry of the flood delta at the entrance to the smaller of the two tidal basins.

Previous studies of areas with similar physiographic features on the Texas coast include the washover fan on northern St. Joseph Island associated with Vinson Slough

(Andrews, 1966, 1970) and the tidal delta at Aransas Pass (Hoover, 1968). I have relied on these studies for some of the specific information on plant communities, sediment facies and limiting elevation of environments summarized in Appendix E. Terms used for physiographic features on the flood delta at Pass Cavallo as much as possible follow usage by Andrews, and Hoover. Appendix F is a correlation of physiographic terms used in this study with terms used by Andrews and by Hoover. Map units were compared to Tobin aerial mosaics of each study area to make the correlation charts.

Physiographic Provinces of the Flood Delta

The flood delta at Pass Cavallo exhibits geographic variations in sediment composition and geometry of physiographic features. These variations are related to sediment supply and to the magnitude and frequency of currents and waves generated in each body of water adjacent to the flood delta. Thus, I have distinguished three informal physiographic provinces: "Gulf of Mexico Province," "Matagorda Bay Province," and "Espiritu Santo Bay Province".

Gulf of Mexico Province.--The inlet-margin shoreline of the flood delta facing the Gulf is exposed to the largest astronomical tidal range of any flood delta shoreline at

Pass Cavallo. The mean diurnal tidal range decreases from about 2 feet at the tip of the axial trough to about 1.5 feet near profile V and Pelican Island--a distance of about 3 miles. Waves out of the Gulf of Mexico are refracted over the Gulf bar and axial trough, which reduces wave energy so that there is usually a single line of breakers along the inlet-margin shoreline, instead of the 2-3 at the open Gulf beach on Matagorda Island and Matagorda Peninsula (frontispiece). Also, this shoreline is exposed to the full brunt of hurricane and tropical storm surge and waves. As a result, this province has the best-developed and largest intertidal beaches, surge channels, storm-tidal flats and mounds of all three flood delta provinces.

The inlet-margin Gulf beach on Plate I was mapped at a time (1957) when littoral drift was dominantly northward and the intertidal beach was constructional. Note that this sandy beach and shoal does not extend far north of profile V (Fig. 17, 1957; Plate I). On several charts (e.g., 1965 edition, and Nov. 1971) and on the U.S.G.S. topographic map of Pass Cavallo (1952 ed.) this beach was discontinuous or absent north of Profile VI. A constructional sand beach also was absent at Profile V and VI in March 1972, almost 7 months after hurricane Fern struck this area, although bars present on the shoal

Figure 17

Aerial mosaics of the Gulf of Mexico Province including Fish Pond, Mule Slough and Big Pocket between profiles V and VI in 1934 and 1957. Profile V is opposite Pelican Island on the Gulf bar.

1934

1957

Figure 17

indicate sand was being moved shoreward (Fig. 18). The alternate presence and absence of the intertidal sand beach suggests that this beach is destroyed during tropical cyclones and returns between storms. Probably sand is supplied to construct this beach by northward littoral drift from the open Gulf beach and inlet-margin shoal.

The largest and deepest surge channels on the flood delta are Mule Slough and Fish Pond between Profiles V and VI (Plate I and Fig. 17). Fish Pond and the southern arm of Mule Slough are about 1 mile long and about 1000 feet wide close to Pass Cavallo. Depth in Fish Pond and Mule Slough are mostly less than 3 feet but near Pass Cavallo may exceed 6 feet. These two surge channels are large enough to serve as tidal basins for very small inlets which remain open to Pass Cavallo across the inlet-margin Gulf beach for several months following storms (Fig. 17).

Several factors contribute to the large size of surge channels open to the Gulf versus those open to Matagorda Bay (Plate I). Probably the most important is that the highest tides and most destructive waves occur during hurricanes approaching from the Gulf. However, another important reason for the size of channels is that vegetated mounds bordering Fish Pond and Mule Slough are

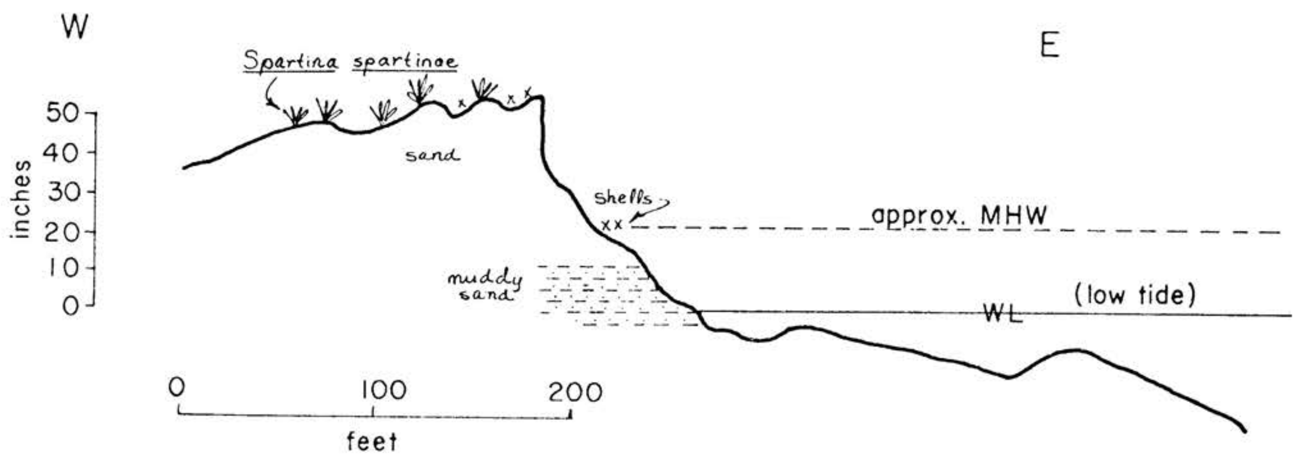


Figure 18. Erosional storm beach and shoal facing the Gulf of Mexico at Mexico at profile V in March 1972.

higher and longer than most of the mounds north of Profile V so that they better confine the flow.

Vertical accretion of mounds on the flood delta to a maximum height of 5-6 feet above mean high water level (MHW) is probably due to currents during extremely high hurricane tides of infrequent occurance. And due to the abundant sand supply more mounds in the Gulf province are high mounds than opposite Matagorda Bay. Figure 17 shows the mound at Profile V in 1934 and 1957. Although about one-third of its length was eroded by 1957, the mound developed a distinct outline of dense, high mound vegetation (greater than 4-6 feet above MHW), where before vegetation had been sparse or nonexistent (less than 2-3 feet above MHW). Because this mound is bordered on two sides by water-filled surge channels and on the east by a low intertidal beach, it is unlikely that wind blown sand is responsible for this accretion.

Eolian processes may not be important on the flood delta at Pass Cavallo because vegetation stabilizes mounds and storm-tidal flats are frequently inundated. The only active dunes recognized on the flood delta in 1957 were small coppice dunes located at the mound front at Profile VI. Sand blown from the beach at Pass Cavallo, when the beach was present, would accumulate at the mound front or blow into Fish Pond or Mule Slough. None of this sand would reach the mound tops or storm-tidal flat. During droughts sand might be eroded from storm-tidal flats and transported onto mounds but generally storm-tidal flat sediments are bound by mats of filimentous algae (Hoover, 1968). Wind may winnow sand from the surface of sparsely vegetated, low mounds during dry years to produce shell layers, although currents during falling storm tides may be sufficient to concentrate shell as they lose competence to move shell.

Shell layers may separate depositional events that formed the mounds. One or more of these shell layers were found in trenches through high mound sediments at Profiles V and VI and at trench (Plate I) that were overlain by homogeneous, root-mottled sand 0.5 to 2.0 feet thick.

Once mounds attain an elevation of 5-6 feet above mean high water they are apparently stable with respect to height and outline. For example, the mounds at Profile VI north of Fish Pond have had the same recognizable outline since about 1860 (Coast Chart 208, 1918 ed.). Yet a trench dug in the high mound at Profile VI adjacent to the storm beach uncovered a copper wire at about 28 inches that may be a remnant of a fort near that location in the early 1800's (Bruce Wilkenson, 1972, personal communication). This indicates that this mound may have gained elevation quickly at the beginning of the 19th century and then maintained almost the same outline, and possibly elevation, for at least 100 years. Erosion of the mound front adjacent to Pass Cavallo has been the only major change detected since 1860.

The subtle relationship of surge channels to storm-tidal flats is shown at Mule Slough. Mule Slough is the northern and largest part of a complex surge channel that enters between the mounds at Profiles V and VI and divides at small high mound slightly inland from these profiles. The distal margin of Mule Slough grades into low storm-tidal flats and then into unvegetated subtidal flats at Big Pocket, much of which may be submerged most of the time. Note the changes between 1934 and 1957 in dimensions of this surge channel and low, unvegetated mounds, and also in the surface features on the storm-tidal flats due to hurricane tides (Fig. 17 and Plate I).

The distance that sand is transported from the inlet-margin Gulf beach depends on the storm flood discharge, or rate of rise and the height reached by the surge. During the highest effective tides, sand is transported all the way to Espiritu Santo Bay at Big Pocket, a distance of 7000 to 8000 feet (Plate I). This is indicated by numerous bars oriented parallel to the long axis of Mule Slough that occur along the margin of storm-tidal flat at Big Pocket. A curving line of bars in Mule Slough about 4000 feet from the shoreline in 1934 indicates that sand is transported only part way to Big Pocket during lesser storm tides (Fig. 17). Salt marsh is poorly developed in Big Pocket, and is located only where bordered by about 1000 feet of low, storm-tidal flat.

Between 1934 and 1957, four hurricanes struck near Pass Cavallo to produce tides greater than 5 feet above mean sea level--an average of one storm every 5 years during that 23 year period (Price 1956b). All 4 hurricanes probably were capable of transporting some sand to Big Pocket in Espiritu Santo Bay. An analysis of possible hydraulic parameters of Fish Pond (similar to method in Appendix D) suggest that tides of about 5-6 feet above mean high water (MHW) may be sufficient to maintain that surge channel length and deposit bars (or low mounds) about 7000 feet from the Gulf shoreline. An effective hurricane tide of about 5 feet also is coincident with the maximum mound height on the flood delta at about 5 feet.

Rate of accumulation of sediment on and at the margins of storm-tidal flats is very slow in spite of the tremendous energy in a single hurricane. Very little change in shoreline shape at Big Pocket can be detected since surveys made about 1860, even though this is one of the more active washover areas on the flood delta, Scott, et al. (1969) found that most of the sediment carried by surge channels on Padre Island and at Vinson Slough on St. Joseph Island was eroded from the beach at the entrance to the surge channel. Erosion of the beach blocking the channel (when the beach is present) provides a small plug of sediment relative to the large surface area of the flat so that only a thin veneer of sand and shell is deposited by any one storm. Mud is supplied to storm-tidal flats and surge channels during hurricane ebb and lesser wind tides when muddy bay water fills depressions on the flats and fines settle out (Hoover, 1968). Consequently, the sediment in this province is dominantly fine quartz sand, supplied from the inlet-margin Gulf beach with mud content towards Espiritu Santo Bay.

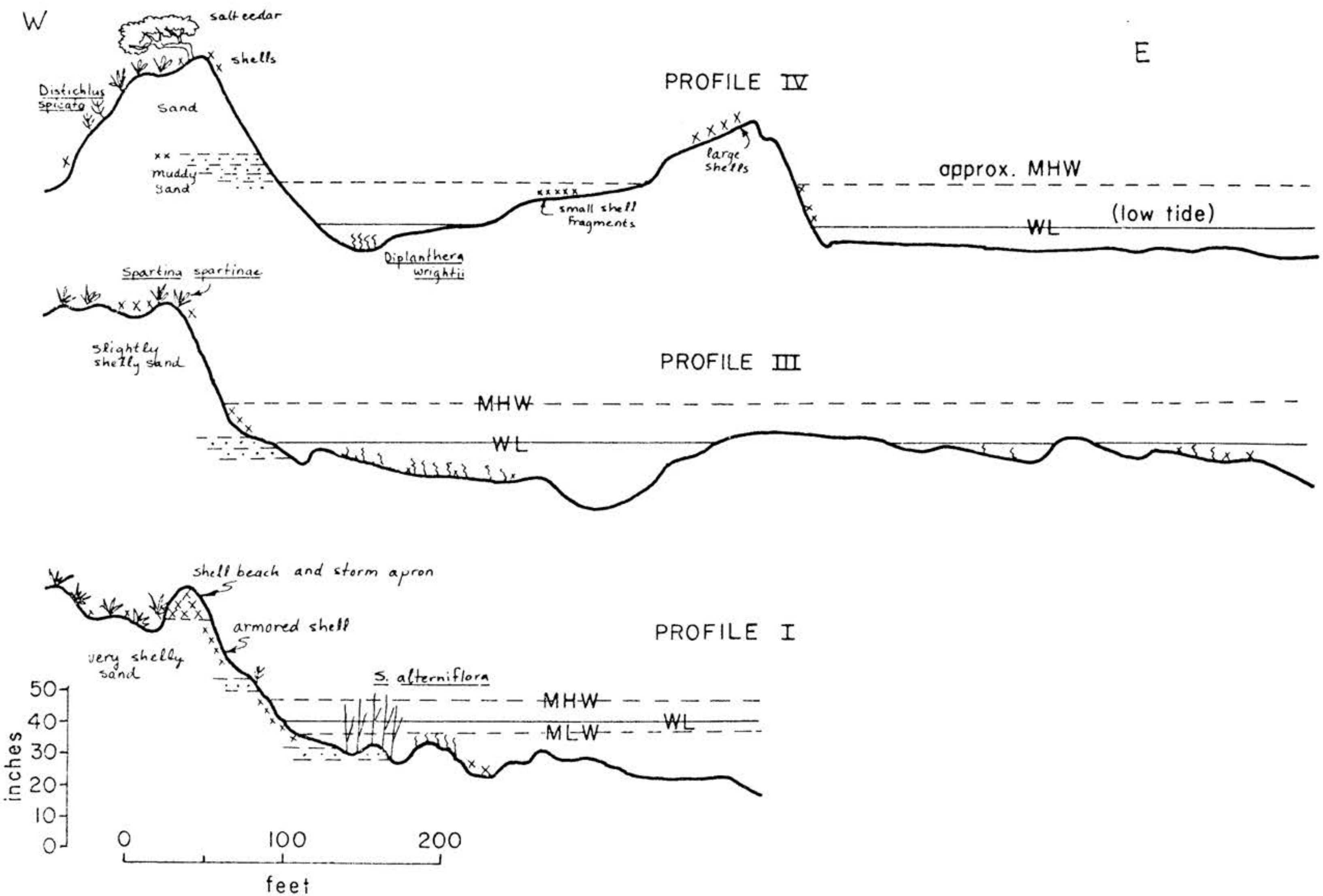
Matagorda Bay Provence.--Along the inlet-margin shoreline of Matagorda Bay the diurnal tidal range decreases from about 1.4 feet at Saluria Bayou to about 1.1 feet near Port O'Connor. This shoreline is relatively protected from southerly waves by the Gulf bar and Matagorda Peninsula. Consequently, the only wave activity affecting these shorelines probably occurs with northers between September through May, and during hurricanes with easterly or northerly winds. The fetch across Matagorda Bay is 15 to 20 miles, which is sufficient for winds to generate high wind tides and waves.

Construction of jetties about 1918 and also about 1940 across the sandy inlet-margin shoal near Port O'Connor interrupted transport of sediment southward. How much these jetties have disrupted the Matagorda Bay province is uncertain, but there is some evidence to suggest that smooth shorelines were nearly continuous from Port O'Connor to Matagorda Island before 1900. Before 1900 inlet-margin shorelines in Matagorda Bay were surveyed fairly straight; whereas after 1934, these shorelines are shown as more uneven and less distinct (Frontispiece; Figs. 12 and 13). Shoreline erosion also apparently accelerated after 1934 (Table 6).

In 1957 (Plate I) and March 1972, there were no intertidal, constructional beaches along the Matagorda Bay shoreline of the flood delta. Profiles I, III and IV had steep slopes on mound fronts eroded by storm waves (Fig. 19). Profile II (not shown) was similar except that the steep, storm beach was cut into a washover storm apron composed of shelly sand (and mapped as low mound on Plate I). At profile IV, an emergent bar was located about 200 feet offshore from

Figure 19

Comparison of three storm beaches and shoals facing Matagorda Bay. All profiles are from mounds (west) towards Pass Cavallo (east). Profiles were made during March 16-21, 1972.


W
E
saltcedar
shells
Distichlus spicata
Sand
PROFILE IV
large shells
approx. MHW
muddy sand
small shell fragments
WL
(low tide)
Diplanthera wrightii
Spartina spartinae
slightly shelly sand
PROFILE III
MHW
WL
shell beach and storm apron
armored shell
PROFILE I
very shelly sand
S. alterniflora
MHW
MLW
WL
50
40
30
20
10
0
inches
0
100
200
feet

the mound; but even the inlet side of this bar had a steep erosional beach face (Fig. 19). Debris lines and zones of swash-deposited shell marked the intertidal zone on these storm beaches in March 1972.

The offshore bar at profile IV was about 3 feet above water level in March and extended over 1000 feet from profile IV to the Coast Guard ruins on Saluria Bayou (Fig. 18). I observed this bar during a norther in December 1971 when the top was barely submerged at high tide and wave activity was moderate. Wave action during winter storms probably was responsible for the steep, erosional face on the inlet side of the bar in March, and plantation of the shoal. This bar apparently formed when tides were greater than 4 feet during hurricane Fern in September 1971. Fern passed southwest over Pass Cavallo with wind speeds in excess of 60 mph near the eye (DeAngelis, 1971). In August 1971, a small bar was emergent on the outer edge of the shoal adjacent to the axial trough (frontispiece). This small bar probably was pushed shoreward by Fern to become the nucleus of the long, emergent bar observed in December 1971.

Emergent storm bars close to the storm beach such as the one at profile IV and storm beaches that developed on storm aprons linking mounds probably formed the smooth flood delta shoreline in Matagorda Bay prior to 1900. Possibly the greater length of these storm beaches and bars was due to a slightly greater sediment supply from the north. However, waves in Matagorda Bay could not have been any more competent a century ago than they are now to move sand shoreward between storms to construct an intertidal sand beach. In fact, very little recent agitation of the inlet-margin shoal was observed in March 1972. The sand composing the shoal was dark gray below the surface and only the top .25 inch was oxidized a light brown color; even on the broad shallow bar at profile III (Fig. 19).

The presence of two large tidal channels, Big Bayou and Saluria Bayou, behind the Gulf bar suggests that sand was not as abundant in this province before 1900 as in the Gulf of Mexico province. A larger supply of sand might have clogged these channels. Another indication that sand has never been very abundant in this province is that sediment composition of mounds changes from sand with very little shell at profile IV to very shelly sand (or sandy shell) at profile I. So much shell in fact, that shell may have been an important constituent of sediment supplied to the flood delta from the west shoreline of Matagorda Bay.

The long term effect of the jetties near Port O'Connor has been to cannabilize sand from mounds and storm aprons to produce rapid shoreline retreat especially at profile III and IV (Table 6). On plate I facing Matagorda Bay storm aprons are connected to mounds at profiles II and III, and the unvegetated inlet-margin shoal is located only opposite mounds. This indicates that storm waves predominantly remove sand from mounds and deposit it offshore on the shoal or literally to a storm apron.

Inlet-margin shoals vegetated with seagrasses are located in areas relatively sheltered from northers between mounds, and at the southeast corner of salt marsh islands such as Bayucos Island north of Saluria Bayou in 1957 (Plate I and Appendix E). During summer when wave activity is light, transverse bars at the deeper edge of the shoal are mostly inactive, so that seagrasses, mostly <u>Thalassia testudinum</u>, probably colonize them (Hoover, 1968). In contrast, the 1934 photomosaics of the flood delta show no seagrass development on shoals next to Pass Cavallo. Possibly the absence of vegetated shoals in 1934 indicates that the entire shoal area was reworked during the summer growing season by tropical storms that struck elsewhere on the coast in July and August, 1934 (Price, 1956b).

Figure 20

Three photographs of the flood delta near the Coast Guard ruins at Saluria Bayou in December 1971. Time was morning low tide during a "norther".

A. Surge runway (storm tidal flat) looking east towards Pass Cavallo and Coast Guard ruins. Scours in foreground developed through algae-bound sand by storm surge. Note rip-up clasts and sand ripples west of scours.

B. Low mound west of Coast Guard ruins vegetated with Monanthochloë littoralis. View is west towards a flooded surge runway off Saluria Bayou.

C. Inlet-margin storm beach at profile IV in December 1971 during a norther. View is south at morning low tide. The long, emergent offshore bar is visible on the horizon. Note the muddy sand underlying the mound and the Spartina alterniflora exposed at low tide. Profile IV passed near the salt cedar on top of the high mound in the right center of the photograph.

A

B

C

Figure 20

Some sand is distributed to storm-tidal flats and inland mounds of the Matagorda Bay province during northers and tropical storms. In 1934, the high mound at profile IV was connected by low mound to the high mound on which the Coast Guard station is located. Between 1934 and 1957 the shoreline retreated about 300 feet (Table 6) and a storm runway (or storm-tidal flat) was carved through this low mound (Fig. 20A). The runway is lying on exhumed storm-tidal flat sediments that had been buried by low mound sound (Fig. 18). New mounds then formed on either side of the surge runway or storm-tidal flat about 1000-2000 feet west of the high mounds at the Coast Guard ruins and profile IV (Fig. 17B). In one of these new mounds adjacent to the Coast Guard ruins, that was low mound in 1957 and high mound in 1972, copper sheets were uncovered about 15 inches below the surface. Apparently this mound had accreted vertically almost 1.5 feet in 15 years. Most of this growth may have been due to hurricane Carla, one of the largest of this century, that struck Pass Cavallo in September 1961 with 15-foot tides in the Gulf of Mexico.

Mounds in the Matagorda Bay province tend to be complexes of high vegetated mounds near Pass Cavallo and low, sparsely vegetated mounds away from the inlet. Most of these complexes are composed of low mounds, and as a consequence change position and elevation from storm to storm, and are indistinctly outlined compared to high mounds in the Gulf province. Most mounds are located adjacent to the inlet-margin shoreline of the flood delta. However, two, elongate mound complexes in the Matagorda Bay province are located several thousand feet inland from the inlet shoreline. These isolated mounds are located on either side of Saluria Bayou and may indicate how long, elongate mounds initially form (XI on Plate I, and the first mound north of Saluria Bayou). These elongate mounds apparently formed where surge currents, moving along two surge runways or storm-tidal flats, spread out, converged and dropped their load. Successive storms would smooth the outline of such mounds, accrete sparsely vegetated parts and deposit sand in the lee behind the mound.

Surge channels are also smaller in this province and less distinct than in the Gulf province partly because mounds are smaller and do not confine the surge as well. Surge channels north of profile V average about 1000 feet long, 100 feet wide, and appear to be less than 1-2 feet deep if they exist at all. Some of the deeper depressions but less persistent on photographs were filled with seagrasses (probably Diplanthera wrightii) especially between profiles IV and V. However, channels and ponds north of Saluria Bayou tend to have persistent outlines. For example, the surge channel just north of the mound at profile III and the chain of ponds on either side of the mound at profile I have not changed shape or size since 1934.

The Matagorda Bay province is similar to the Gulf of Mexico province in types of physiographic features, except that these features are less well-developed. A lack of abundant sand supply and a reduction in frequent wave action prevents the construction of intertidal beaches that in turn feed storm-tidal flats and mounds. As a result, mounds contain more shell northward towards profile I, and storm-tidal flats contain more mud and encroaching salt marsh than in the Gulf province.

<u>Espiritu Santo Bay Province</u>.--Espiritu Santo Bay is a small tidal basin relative to Matagorda Bay. The diurnal tidal range in Espiritu Santo Bay is about .3 foot compared to 1.1 foot in Matagorda Bay, and the fetch for wind-generated tides and waves is short--usually less than 2 miles compared to 10-20 miles in Matagorda Bay. As a result, beaches and straight shorelines form only where fetch for northerly or southerly winds is greater than 1 mile. Salt marsh or storm-tidal flat are located at uneven shorelines that are opposite a short fetch for strong winds, or face a westerly direction from which

strong winds are not common on the Texas coast. Mud is the most common constituent in sediments along the margin of Espiritu Santo Bay with the exception of shell beaches and sand shoals on north-facing shorelines from which mud has been removed by wave action.

Straight shorelines 1-2 miles long are oriented northeast on northern Bayucos Island and Grass Island, and on both sides of Farwell Island (Plate I). The northeast orientation of most straight shorelines indicates that there is a dominant component of wind and waves from the northwest (King, 1959, p. 259). This is partly due to the unobstructed fetch from that direction across Espiritu Santo Bay (Plate I). The east-west orientation of small spits at Bayucos Point superimposed on this northeast-trending shoreline indicates that wind and waves from north and northeast (during northers) probably are more frequent than wind and waves from the northwest. The low frequency of wind from the northwest is also indicated by the dominance of winds from north and northeast and southeast at Victoria, Texas (Appendix A). In fact, strong northwest winds probably occur only when the eye of a tropical cyclone passes northeast of Pass Cavallo and during the first hours of a norther (E. W. Behrens, 1972, personal communication).

Apparently these wind speeds more than make up for their low frequency in orienting the shoreline.

The straight shorelines on Bayucos Island and Grass Island are composed of salt marsh towards the northeast and shell beaches with storm aprons southwestward (Plate I). Accumulation of shell beaches towards the southwest indicates that the dominant direction of shell transport by waves is towards the southwest. Also these storm beaches are usually made up of a series of shell spits recurved southwestward. At Bayucos Point, enechelon, small spits about 100-200 feet long are oriented east and west on the northeast-trending shoreline. Profile VII at Bayucos Point was made across two of these shell spits. At Grass Island, successive shell spits oriented more northeast-southwest are 1000-2000 feet long. The most recent spit on Grass Island was built almost 1000 feet from the southwest tip of the island since 1873. On Farwell Island shell beaches without spits compose the straight north and south shoreline.

Comparison of shoreline surveys made about 1873 with Coast Chart 889 (1965 ed.) indicates that north-facing straight shorelines have retreated about 100 feet over the past century. And the shoal in front of these shorelines (outlined by the 3-foot depth contour) has also retreated about an equal amount. The largest change occurred at the easternmost 4000 feet of straight shoreline on Bayucos Island (Plate I). At that location the 3-foot depth contour retreated about 400 feet and the shoreline almost as much. Erosion of this shoal may have supplied the abundant shell to the southwestern shell beaches and storm aprons to accrete the numerous shell spits at Bayucos Point. Mollusc species typical of oyster clumps and grassflats that Bruce Wilkenson and I recognized on these shell beaches also indicate that the shell source is from the shoal (Hoover, 1968; Parker, 1960).

Unlike other physiographic provinces on the flood delta the dominant physiographic feature in the Espiritu Santo Bay province is salt marsh. The larger areas of salt marsh are due to the long intervals between hurricanes and to the lack of other processes in the lagoon, except for 15-20 northers each year that affect north-facing shorelines. Salt marsh apparently colonizes hurricane bars and unvegetated subtidal flats where sheltered from most storm waves and currents. Salt marsh on Grass Island, for example, probably grew southwestward behind each successive shell spit (Plate I). And some salt marsh behind the shell beach and storm apron on Bayucos Point is new since 1873 (Fig. 21).

Shell beaches in Espiritu Santo Bay usually are located above the intertidal zone or line of approximate

Figure 21

Shell beach and storm apron on Bayucos Point in December 1971 during a "norther".

A. View north of shell beach with several steps. The top 2 or 3 steps are composed of unsorted shell. The active swash zone is composed of smaller, relatively sorted shell fragments with a small step of shell and grass debris forming at the top of the swash.

B. View north of storm apron formed when hurricane tides and northerly wind waves wash over the shell beach.

A

B

Figure 21

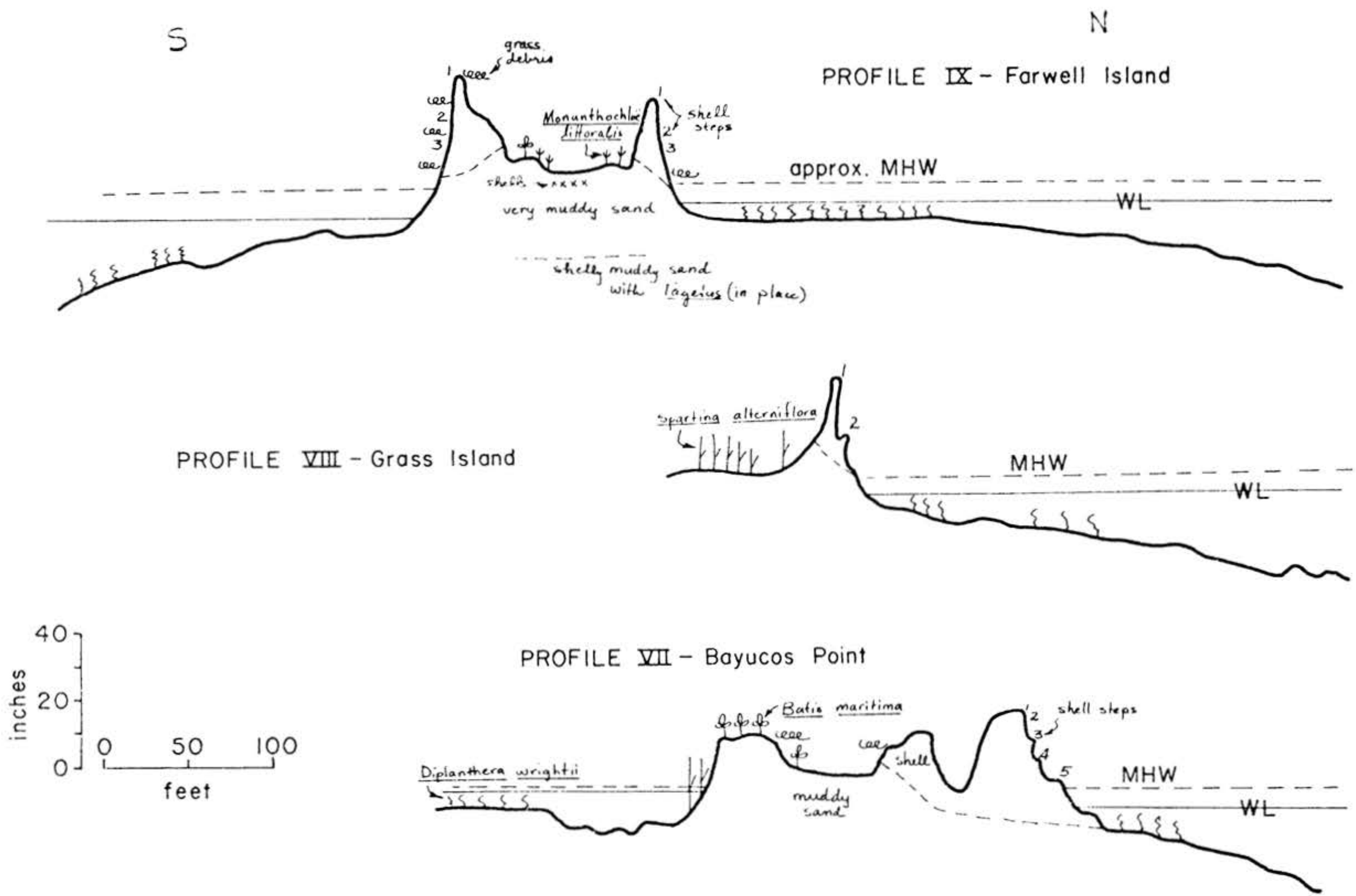
mean high water (Fig. 20). Above this water line the beach is composed of loose shell and sand with numerous steps or ridges of shell and other debris (Figs. 21 and 22). Unlike the composite shingle beach in Figure 23 which is mostly intertidal, the upper beach in Espiritu Santo Bay is active only during storm tides above mean astronomical high tide. Below this approximate mean high water line the beach slope is cut into shelly muddy sand or sandy shell, the surface of which usually is littered or armored with large shells.

Storm aprons from behind the shell beach during tropical storms or extreme northers when tides are higher than the storm beach. At that time shell and sand are eroded from the beach and shoal, and wash over the apron to be deposited on the distal avalanche face (Fig. 20B). Hoover (1968, p. 19-26) observed similar storm aprons at the margin of Harbor Island and Aransas Bay before and after 6.6-foot tides accompanying hurricane Beulah in September 1967. The crest of the storm apron in Aransas Bay probably was submerged about 2 feet and also wave activity was heavy. The net effect of this storm was to erode shell from the front of the beach and move landward submerged, shell-rich bars to accrete the storm apron.

Shell beaches and storm aprons only form on the Texas coast where there is a low sand supply. And in

Figure 22

Comparison of shell beaches and storm aprons on Farwell Island, Grass Island and Bayucos Point in Espiritu Santo Bay. Profiles are aligned from about the 2 foot depth off the north beach. The double apron at Bayucos Point is due to a recurred spit that formed in front of the old storm apron. The shell was derived from an eroded beach immediately east of profile VII. The diurnal tidal range in Espiritu Santo Bay is about 3 feet.


S
N
PROFILE IX - Farwell Island
grass debris
Monanthochloë littoralis
shell steps
approx. MHW
WL
shell
very muddy sand
shelly muddy sand with Tagelus (in place)
PROFILE VIII - Grass Island
Spartina alterniflora
MHW
WL
PROFILE VII - Bayucos Point
Batis maritima
shell steps
shell
muddy sand
Diplanthera wrightii
MHW
WL
inches
40
20
0
0 50 100
feet

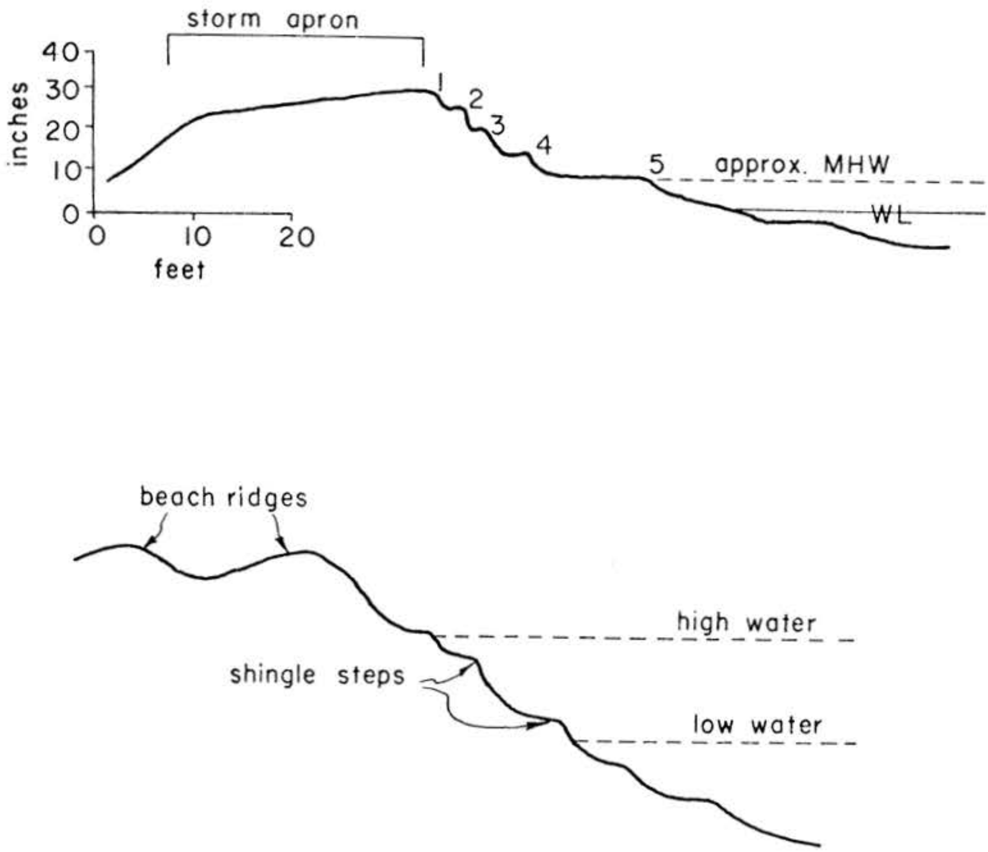


Figure 23. Comparison of the shell beach and storm apron at profile VII on Bayucos Point with a composite shingle beach profile of unknown scale. (King, 1959, p. 49). The shell beach on Bayucos Point is mostly active during storm tides 1 to 3 feet above the water level in March 1972. Storm tide levels higher than step 2 overwash the beach to produce the storm apron.

the Espiritu Santo Bay province, sand is supplied from the Gulf province only during hurricanes with large tides. At other times sand is supplied by erosion of shorelines. The fairly discrete separation of sand, shell and mud in the vicinity of shell beaches and storm aprons probably is due to the "competence" of waves of certain steepness to erode and transport certain size materials. Mud is suspended by almost any wave activity and removed from the beach and shoal. Waves that would be destructive on sand beaches may be constructive on shell beaches (King, 1959, p. 250). This would explain why shell is dominant on the storm beach even though sand and mud are generally more abundant materials on the shoal and in adjacent salt marsh. Shell beaches probably act as "sinks" for shell. At any one spot the shell in the beach may vary in age from the time of initial formation of the flood delta to the last storm capable of eroding living molluscs from the shoal in front of the beach.

The submerged flood delta platform in Espiritu Santo Bay is outlined by the 6-foot depth contour (Plate I). Coast charts of Espiritu Santo Bay in 1873 and 1965 indicate that depths greater than 4-6 feet are composed of soft mud, and depths less than 3 feet are hard sand. Shepard and Moore (1960, p. 135) also indicate that the deeper parts of central Texas bays and lagoons are silty clay while the bay margins (less than 3 feet deep) are mostly sand, or muddy sand.

The most pronounced bulges of the flood delta platform in Espiritu Santo Bay are located opposite the stable, marsh-lined channels, Saluria Bayou and Big Bayou. Oyster feefs and extensive grassflats are located at the distal ends of these large tidal channels in Espiritu Santo Bay (Plate I). Some shoaling of about 0.5 foot or more had occurred between 1873 and 1934 at most places on the flood delta platform except along straight erosional shorelines. Most areas with shoaling greater than 1.0 foot are located opposite the distal ends of Big Bayou and Saluria Bayou. The only other areas on the platform, where shoaling of more than 1.0 foot occurred, are found at the distal margins of the platform at the 6-foot depth contour west of Bayucos Point, Grass Island and Farwell Island.

Normal tidal currents apparently do not transport sand all the way from Pass Cavallo because grassflat sediments are composed mostly of mud or muddy sand. Based on the entrance area of Saluria Bayou at 3450 sq. feet, a discharge computed for spring tide velocities of about 4.2 feet/sec. would transport sand about 5000 feet (Appendix D). And the length of marsh-lined channel is about 9500 feet. The sand that is present in grassflat sediments as far west as Grass Island probably was transported along these channels into Espiritu Santo Bay during hurricane tides and then redistributed to the edge of the platform by storm waves.

The association of shallow lagoon shoals, salt marsh and oyster reefs with Saluria Bayou and Big Bayou is shown in Figure 24 and Plate I. Between 1873 and 1957 new marsh islands established a foothold on depositional shoals in several places in Espiritu Santo Bay, especially adjacent to Big Bayou and at the distal end of Saluria Bayou at the tip of Bayucos Island. For example, the area of salt marsh north of Big Bayou doubled in size between 1873 and 1957 (Fig. 24). In 1873 a shoal almost 1000 feet wide with 4 marsh islands separated Big Bayou from Barroom Bay. In 1957 salt marsh islands covered most of the shoal with the exception of a few tidal channels and a narrow rim of grassflat in Barroom Bay. The areas of salt marsh in 1957 were about half *Batis maritima* and *Salicornia perennis*, and half *Spartina alterniflora* (Plate I). Other small marsh islands gained a foothold on the shoal south of Big Bayou during those 84 years.

Tops of oyster reefs associated with Saluria and Big Bayous are exposed at normal water levels in Espiritu

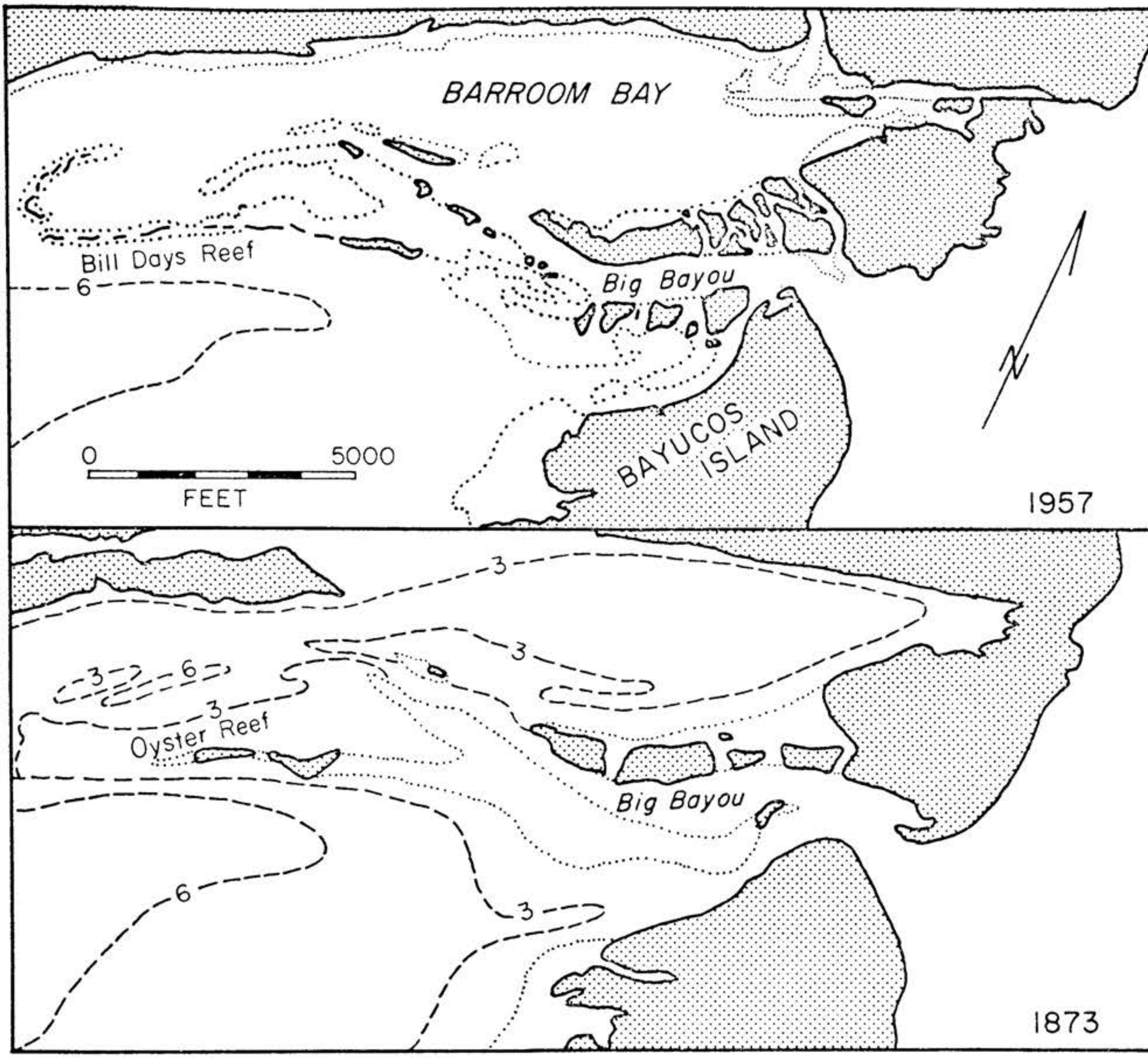


Figure 24. Salt marsh and shoals surrounding Big Bayou in Espiritu Santo Bay in 1873 and 1957. The dotted line in 1873 represents shoal areas less than .5 foot deep during the hydrographic survey. The dotted line in 1957 represents areas of unvegetated subtidal flat and grassflat mostly less than 1.5 to 2 feet deep. Between 1873 and 1957 Bill Days reef (oyster reef) extended 3,000 feet around the tip of the 3-foot shoal and also the amount of salt marsh doubled in area.

Santo Bay (Plate I). These reefs are located on shoals less than 3 feet deep at the distal ends of these channels. Between 1873 and 1957 the oyster reef (known as Bill Day's Reef in 1957) extended about 3000 feet around the tip of the 3-foot shoal at the end of Big Bayou (Fig. 24). The outline of the reef in 1957 was visible on the 1934 serial photographs so that the additional 3000 feet of reef developed in about 61 years. Live oysters may have grown between hurricanes on shell-rich bars built on the 3-foot shoal by strong southeasterly hurricane waves. Large oyster shell and shell fragments are abundant on the reef surface and probably were supplied to bars on the shoal from the existing reef immediately to the east.

Thus, in the Espiritu Santo Bay province evidence for hurricane activity is found mostly in sand content in sediments as far west as Grass Island, and in the elevation and morphology of shell beaches and storm aprons. Storm-generated currents probably bring sand to this province mostly down the large tidal channels and also across storm-tidal flats in the Gulf province. Much of this sediment is resculptured by storm waves to form the nucleus of oyster reefs, shell beaches, Grass Island and Farwell Island, and to prograde the flood delta platform into the lagoon.

SUMMARY AND CONCLUSIONS

The Texas Gulf Coast at Pass Cavallo is characterized by a mean diurnal tidal range of about 2.0 feet. Because the volume of flow through an inlet is proportional to the tidal range in the area of the tidal basin, Texas tidal inlets have some of the largest tidal basins relative to their entrance size of any inlet. Matagorda Bay at Pass Cavallo has an area of about 200 square miles, and a mean diurnal tidal range of about 1.1 feet.

Because the tidal range is small in the Gulf of Mexico and in Matagorda Bay, relative to other coasts, wind tides and storm tides play an important role in modifying water levels near, and currents in Pass Cavallo. In general, the strongest winds at Pass Cavallo are from the south, southeast, north and northeast. The fetch across Matagorda Bay for these winds varies from 10 to 20 miles so that wind tides commonly add or subtract 1 to 2 feet for several days at a time to the astronomical tidal range along the northern and southern bay shoreline. During the period of neap tides each month, wind tides may produce flood or ebb currents for several days depending on the direction of the wind.

Wind tides are especially important during winter, and part of spring and fall when highs and lows move rapidly in an easterly direction across the United States and northern Gulf of Mexico. During summer, south and southeast winds predominate for long periods. Following several successive days of strong southerly winds, water levels rise in Matagorda Bay but not in the Gulf, so that ebb currents through Pass Cavallo are enhanced. This summer pattern is broken only by an infrequent tropical storm or hurricane.

Daily river discharges into Matagorda Bay are too small relative to the volume of water filling Matagorda Bay each tidal cycle to affect the inlet regime. Only flood discharges that occur at 5- to 20-year frequencies on the Lavaca and Colorado Rivers could provide enough water to add even .5 foot to the bay level to affect inlet currents.

Although I recognized the importance of wind tides, I did not specifically study the effect of these tides on inlet currents or on inlet stability. Primarily this was because tide gage data was available from 1967 to 1970, while charts and maps of Pass Cavallo were made prior to 1965. I assumed that wind and storm tides (spring tidal range) and average maximum current velocity to evaluate long-term inlet stability.

Pass Cavallo in each of three time periods passed all tests for inlet stability (cross-sectional area and shape, and material transfer) developed by Brunn and Gerritsen (1960)--with one exception. After 1965, Pass Cavallo exhibited characteristics of both tidal flow by-passing and bar by-passing of littoral drift material. The three time periods for Pass Cavallo were 1856-1930, 1930-1965 and post 1965. Each time period was characterized by a different, and subsequently smaller, cross-sectional area and tidal discharge. These time periods were separated by distinct events. Between 1929 and 1935, the Colorado River delta rapidly built across east Matagorda Bay reducing the tidal area available to Pass Cavallo, and, in 1965, the Matagorda Ship Channel was dredged across Matagorda Peninsula reducing the volume of water passing through the natural inlet (Fig. 2).

Other features that changed with decreasing discharge but remained stable during each time period were:

1) the channel pattern, that decreased from two bay flood channels and two flood bars, to a single flood channel with flood bar after 1930 (Fig. 13)

2) the Gulf bar, that shoaled with each change in discharge, especially between Pelican Island and Matagorda Peninsula, and retreated bayward opposite the axial trough and channels east of Pelican Island, and

3) total channel length, that became progressively shorter during each successive time period (Table 5).

Over the past hundred years, there has been some displacement of inlet shorelines and the axial trough southwestward in the dominant direction of littoral drift (Table 6). However, the net migration rate of shorelines and axial trough together is slow relative to the inlet size--about 1000 feet/100 years or less than 1/10 the width between Matagorda Island and Matagorda Peninsula--so that Pass Cavallo historically exhibits geographic stability as well as geometric stability.

Continued migration of the axial trough at Pass Cavallo southwestward apparently is related to the probability that when disruptions of equilibrium occur--due to northers, hurricanes or permanent decrease in discharge--the direction of littoral drift at that time will be southwest. Shorelines, however, apparently respond more to wave conditions and sediment supply than to decreases in tidal discharges, or movements of the axial trough.

Changes observed in shorelines and axial trough since 1856 are:

1) The axial trough migrated at one end and then the other in each succession time period. This rotational movement produced a net migration southwestward in Matagorda Bay of about 1500 feet at the north end of the axial trough and 800 feet at Saluria Bayou and Pelican Island. South of Pelican Island near the Gulf end of the axial trough, the channel moved back and forth over about 800 feet for no net change.

2) Shoreline erosion along the western shoreline of Pass Cavallo has been in the same direction as movement of the axial trough but at a different rate. Most of the erosion immediately south of Port O'Connor occurred after 1934, indicating that jetties built at Port O'Connor to protect the Intracoastal Waterway, sometime about 1940, interrupted the southward movement of sediment. At Saluria Bayou, 1500 feet of erosion occurred between 1887 and 1934 due to axial trough movement and disruption of sand supply from the south probably due to hurricanes keeping the surge channels open at Fish Pond and Mule Slough and eroding sand from the beach.

3) Shorelines on Matagorda Peninsula are not as closely related to the axial trough as on the western

shore of the pass. On the bay side of Matagorda Peninsula about 1000 feet of erosion occurred when the second bay flood bar disappeared before 1934 that had sheltered that shoreline from waves generated by northers. On the Gulf side of Matagorda Peninsula the beach was eroding about 12 feet/year before 1965 due to generally eroding and sediment poor conditions northeastward. After 1965 when the Ship Channel was dredged through the Peninsula, both the Gulf beach and Decros Point accreted 300 and 2000 feet respectively. This probably was due to some sand from offshore spoil reaching the beach, and due to a smaller cross-section at Pass Cavallo providing shoaling from the Gulf bar.

The flood delta at Pass Cavallo is not associated with the north-trending inlet channels, but is located on the western margin of Pass Cavallo separating the pass from Espiritu Santo Bay, with salt marsh islands, tidal channels and storm-tidal flats. I have divided this flood delta into three physiographic provinces: "Gulf of Mexico Province, "Matagorda Bay Province," and "Espiritu Santo Bay Province". Each province reflects a different sediment supply and energy regime inherent in each bay and in the Gulf. Most of the energy to form and modify this feature is supplied by flood surge and waves of hurricanes, tropical storms and northers. There is no evidence in any of these provinces that normal inlet processes are responsible for the modern flood delta at Pass Cavallo. However, the flood delta exists only because the tidal inlet has maintained the opening between the barrier islands.

A summary of each province is given below.

1) Gulf of Mexico Province borders the pass from Matagorda Island to about opposite Pelican Island and includes Mule Slough and Fish Pond. This area has the largest and best-developed intertidal beaches, surge channels, storm-tidal flats and mounds of all three provinces. Sand is supplied between storms northward from the Gulf beach on Matagorda Island by waves refracting over the Gulf bar. Storms erode this sand from inlet-margin beaches and transport the sand towards Espiritu Santo Bay and onto mounds.

2) Matagorda Bay Province extends from south of Saluria Bayou to the islands south of Port O'Connor. Included within this province are the large tidal channels, Saluria Bayou and Big Bayou, that connect tidally Matagorda Bay and Espiritu Santo Bay. This province is similar to the Gulf province in types of physiographic features except that mounds and storm-tidal flats are less-well-developed. Intertidal beaches do not normally develop because of less frequent wave action and a low sand supply. Mounds in this province become more shell

rich northwards and storm-tidal flats contain more mud and encroaching salt marsh than to the south.

3) Espiritu Santo Bay Province includes all of the flood delta within that bay. Almost all physiographic subdivisions are composed of sandy mud or muddy sand, with the exception of erosional shell beaches, some 4 or 5 feet high, facing long open fetch of 1 to 2 miles. This is the richest area biologically consisting mostly of salt marsh and grassflats. Probably the sand present in this province was transported down the tidal channels and surge channels to Espiritu Santo Bay and then redistributed to the edge of the platform by storm waves.

Conclusions

1) The concepts and tests of inlet stability developed by Brunn and Gerritsen (1960) have the advantages for coastal geologists of providing some estimate of inlet regime at the time of old inlet surveys, if there is some knowledge of the modern astronomical tidal range in the tidal basin. Computed values of tidal prism and tidal discharge can be checked against average current velocities reported for sandy inlets on diurnal and semidiurnal coasts by Brunn (1966).

2) The disadvantages to these tests of inlet stability are that they do not provide enough refinement a) to

predict changes in channel pattern, or b) to predict migration rates and styles of migration. However, I believe these stability tests should be refined for each coast with its separate meterological, tidal and sedimentological conditions. A good place to begin would be the Texas coast, because Texas inlets are dominantly hydraulic and therefore not influenced as much by historical variations in river discharge as inlets on other coasts might be.

3) Channel lengths reflect discharge at Pass Cavallo--a fact that I have not seen observed on other inlets. This may allow use of channel length to evaluate the magnitude and frequency of events (whether a large or small tide) that formed some older surge features such as washover fans and flood deltas. Texas flood deltas appear to be storm surge features associated with exiting breaches in barrier islands at tidal inlets. The association of these storm features at some inlets (e.g., Brown Cedar Cut) may explain why channel lengths have not been previously observed to reflect tidal discharge.

APPENDICES

Appendix A.

List of Tide Gage Records, Matagorda Bay and Pass Cavallo.
* = incomplete records

	North Matagorda Bay	South Matagorda Bay	Gulf	Pass	North Espiritu Santo Bay
	No. 2	No. 7	No. 8	No. 9	No. 10
1967		Aug. *		Aug.	Aug.
		Sept.*		Sept.	Sept.
		Oct. *		Oct.	Oct.
		Nov. *		Nov.	Nov.
		Dec.		Dec.	Dec.
1968		Jan.			Jan.
		Feb.		Feb.	Feb.
		Mar.		Mar.	Mar.
		April	April		April
		May	May		May
		June	June	June	June
		July	July	July	July
	Aug.	Aug.	Aug.	Aug.	Aug.
	Sept.	Sept.	Sept.	Sept.	Sept.
	Oct. *	Oct.			Oct.
	Nov. *	Nov.			Nov.
	Dec.	Dec.			Dec.
1969	Jan.	Jan.			Jan.
	Feb.	Feb.	Feb.		Feb.
	Mar. *	Mar.	Mar.	Mar.	Mar.
	April	April	April	April	April
	May	May	May	May	May
	June	June	June		June
	July	July	July		July
	Aug.	Aug.	Aug.	Aug.	Aug.
	Sept.	Sept.	Sept.	Sept.	Sept.
	Oct.	Oct.	Oct.	Oct.	
	Nov.	Nov.	Nov.	Nov.	
	Dec.	Dec.	Dec.	Dec.	

Appendix A (Continued)

	North Matagorda Bay No. 2	South Matagorda Bay No. 7	Gulf No. 8	Pass No. 9	North Espiritu Santo Bay No. 10
1970		Jan.	Jan.	Jan.	
		Feb.	Feb.	Feb.	
		Mar.	Mar.	Mar.	
	April	April	April		
	May	May	May		
	June	June	June		
	July	July	July		
	Aug.	Aug.	Aug.		
	Sept,	Sept.	Sept.		

Appendix B.

Pass Cavallo's Cross-Sectional Area and Tidal Discharge in 1971

Usually the volume of water filling a tidal basin during each tidal cycle is the same, no matter how many openings there are to that tidal basin (Brunn and Gerritsen, 1960). Because part of Matagorda Bay's tidal prism since 1965 is exchanged through the Matagorda Ship Channel, I have estimated that amount using the following assumptions:

1. The cross-sectional area (A) of the Ship Channel is 30,000 sq. feet (Coast Chart 889-SC, October 1970 ed.).

2. Average maximum current velocities (V) in the Ship Channel are only slightly larger than velocities in the pass--probably about 3.2 feet/sec or (4.35 ft/sec for spring tide discharges). (The U.S. Coast Pilot, 1967, notes that currents in the Ship Channel sometimes reach 3 knots or 4.8 ft/sec). Then, the tidal prism (Ω) through the Ship Channel during half the tidal period (T/2) would be

$$\Omega = V\ A\ T/2$$

or 5.8×10^9 cubic feet during spring tides, and 4.3×10^9 cubic feet during mean tidal range.

The amount of Matagorda Bay's tidal prism contributed by Pass Cavallo after 1965 would be about 7.8×10^9 cubic feet during spring tides and 5.7×10^9 cubic feet during mean tidal ranges. By adding the tidal prism of Espiritu Santo Bay (Appendix C) the computed tidal discharges through Pass Cavallo after 1965 are about 180,000 cubic feet/sec during spring tides and 135,000 cubic feet/sec during mean tidal ranges. Assuming an average maximum velocity of about 4.1 ft/sec during spring tides (3.05 ft/sec for mean tidal range) then the cross-sectional area of Pass Cavallo in 1971 would be about 44,000 sq. feet.

Appendix C

Data for Galveston Entrance, Pass Cavallo and Brown Cedar Cut and Their Tidal Basins (Values are for Spring Tidal Range; Mean Tidal Range Values are in Parentheses).

Inlet and Date	Bay Area a sq.ft.x 10^9	Bay Tidal Range h ft.	Inlet Tidal Prism Ω cu.ft.x 10^9	Inlet Tidal Discharge Q cu.ft./sec x 10^5	Inlet Entrance Area A sq.ft.x 10^4	Current Velocity V ft./sec	Inlet Channel Length Lt ft. x 10^4
Galveston Entrance 1867	Galveston Bay = 14.5 West Bay = 2.65	1.5 (1.1) 1.2 (0.9)	24.9 (18.4)	5.5 (4.0)	14.5	3.8 (2.78)	8.7
Pass Cavallo 1856	Matagorda Bay = 10.9 Espiritu Santo Bay = 1.2	1.5 (1.1) 0.45 (0.3)	16.9 (12.4)	3.76 (2.74)	8.945	4.2 (3.06)	6.9
1874					7.04	5.14 (3.89)	---
1887					8.80	4.3 (3.12)	7.7
1934	Matagorda Bay = 9.1	"	14.14 (10.4)	3.14 (2.3)	7.63	4.1 (3.02)	6.2
1965					7.15	4.4 (3.15)	6.0
1971* (App. B)	"	"	8.34 (6.10)	1.80 (1.35)	4.4	4.2 (3.1) assumed	4.3
Brown Cedar Cut 1971	E. Matagorda Bay = 1.5	0.32 (0.24)	4.8 (3.6)	1.06 (0.8)	0.248	4.35 (3.22)	0.6

Appendix D.

Use of channel lengths to determine approximate storm discharge discharge for surge channels and flood delta channel systems.

The importance of channel length measurements is that they apparently are sensitive to discharges that flow from a confined entrance. Thus, approximate hurricane discharges that produced the channel patterns on washover fans and flood deltas can be calculated assuming that the channel lengths are in equilibrium with maximum storm discharge. Having a discharge, the entrance area and hurricane tides responsible can be estimated using topographic maps and the equations in text.

Flow will be confined only when the tides are below the height of the dune wall or mounds on the barrier islands. Otherwise the tide will disperse randomly over the barriers at lesser velocities. Thus the physiography of the barriers will determine the magnitude of the discharge and channel system possible at a given site. Probably this is why tidal deltas do not occur opposite the prominent flood channels at Pass Cavallo and Galveston Entrance. At both inlets tides over 5 to 7 feet above MHW would overtop one or both of the barriers so that the flow would no longer be confined. However, where there is a relatively high dune wall, and the present inlet is very small (if it exists at all), then higher tides could significantly produce a larger discharge and flood delta beyond the reach of normal astronomical currents. Apparently this has happened at the washover fan on St. Joseph Island associated with Vinson Slough and at Brown Cedar Cut.

Brown Cedar Cut.--The history of Brown Cedar Cut provides an example of the relationship of inlet channel length to variable discharges. Brown Cedar Cut first was opened by a hurricane about 1930 (Mason and Sorensen, 1971, p. 25). At that time the barrier was about 3000 feet wide. Between 1930 and 1935 the Gulf shoreline of Matagorda Peninsula eroded due to interference in littoral drift from the north (Ibid., p. 22), and Brown Cedar Cut widened its opening on both sides of the barrier. In 1935 the inlet was about 600 feet wide at its narrowest point and may have averaged about 6 feet deep (Coast Chart 1284, 1939 ed.). For an entrance area of about 3600 sq. feet, the spring tide discharge may have been about 14,500 cu. ft/sec. Thus, in 1935 $Q_{max}L_t$ may have been between 4 and 5 ft^2/sec if the effective total channel length was about 3000 to 4000 feet. After about 1957, however, Brown Cedar Cut tended to show a reduced tidal discharge in that the channel was narrower, and the offset of the barriers and a protruding Gulf bar were no longer prominent (Mason and Sorensen, 1971, p. 38). By 1964 or 1965 the inlet had closed. Shoaling and closing of Brown Cedar Cut may indicate that prolongation of the channel from about 3000 feet initially to about 6000 feet by southwestward migration of the inlet mouth had increased channel length beyond stable values. Development of subaerial islands on the tidal delta during hurricane discharges may also have fixed position of channels in East Matagorda Bay to elongate the channel. High tides from Hurricane Beulah reopened the inlet in 1967, but the entrance area and discharge in 1971 were still smaller than in 1935 (Appendix C).

Mason and Sorensen (1971, p. 63) use a total channel length of about 6000 feet for Brown Cedar Cut in 1971. This was about the total length of the deepest and widest channels in 1958 (Ibid., Fig. 16, 9. 40), yet the total length of channels incised into the tidal delta in 1958, and even on the coast chart in 1935 was about 10,000 feet. However, if a value of Q_{max}/L_t of 4-5 $ft^2/$ represents stability, then the optimum channel length at Brown Cedar Cut in 1971 should have been 2100-2600 feet. This is almost equal to the barrier width. Even in 1935, Brown Cedar Cut would have had an optimum channel length of only about 3000 feet. Thus, most of the visible channels at Brown Cedar Cut are not related to spring tide discharges. Probably most of the tidal delta and total channel length resulted from higher hurricane discharges.

At Brown Cedar Cut, the total length of channels on the flood delta is about 10,000 feet so that a stable hurricane discharge would be about 50,000 cu. ft/sec. During these discharges Brown Cedar Cut apparently has two entering surge channels, one at the site of the inlet channel and one east of it that is normally closed (Mason and Sorensen, 1971, Fig. 16, p. 40). The width between these two channels on the photographs is about 3000 feet. A topographic map made by Mason and Sorensen (1971, Fig. 70, p. 159) shows that this area has a maximum elevation of about 4 feet above their MSL. Tides 3 to 4 feet above MHW would enter through a cross-sectional area of about 12,000 square feet with velocities of about 4.15 feet/sec., using a discharge of about 50,000 cu. ft/sec.

<u>Washover Fan on St. Joseph Island associated with Vinson Slough</u>.-- The washover fan on northern St. Joseph Island studied by Andrews (1966, 1970) is a much larger feature than the flood delta at Brown Cedar Cut. The total length of connected channels holding ponded water is about 42,000 feet (U.S.G.S. 7 1/2 minute topographic maps: St. Charles Bay SE and SW, 1952 ed.). More channel length might be measured on photographs since bar-like mounds are found closer to the fan margin. However, a

"stable" discharge relative to this total channel length is about 210,000 cu. ft/sec. This is about the computed discharge at spring tide conditions for Pass Cavallo in 1971. The dune wall on the barriers adjacent to this channel system is mostly over 10 feet above MHW, and the width of Vinson Slough is about 2500 feet. Tides about 10 feet above MHW scouring about 10 feet deep at the entrance would enter through a cross-sectional area of about 50,000 sq. feet with velocities of about 4.2 ft/sec. The plug of sand that was removed from the entrance would be distributed over the fan margin. Apparently this happened with the 1929 hurricane that went ashore near Vinson Slough (Price, 1956b). The 1934 photographs show rhomboid-shaped flood bars at the distal ends of the surge channels (Fig. D-1). Tides of about 5 feet at this site during Hurricane Beulah in 1967 transported sand only part way along the channel length (Scott, et. al., 1967). Wind transport between storms disperses some of this sand to the mounds and fan margin (Andrews, 1966, 1970; Scott et al., 1969).

There are differences in the channel patterns at the St. Joseph washover fan and at Brown Cedar Cut. Primarily these seem to be due to differences in the height of dunes and in the width of the barriers, and thus to the magnitude and frequency of the events that formed them.

Figure D-1

Outer part of washover fan on northern St. Joseph Island associated with Vinson Slough in 1934. Note rhomboid-shaped bars at distal ends of surge channels.

Vinson Slough

Figure D-1

At the washover far on northern St. Joseph's, almost all of the feature is above mean water level, with the exception of the channels nearest the Gulf, and the channels are straighter. Probably this is because tides of 10 feet or more are almost certainly those of hurricane surge accompanying near passage of the eye. The frequency with which a hurricane strikes this area is not great. A look at storm paths in Price (1956b) and Sugg and Carrodus (1969) suggest that 10 foot tides might occur at Vinson Slough every 20-30 days. At Brown Cedar Cut, however, channels meander more and most of the flood delta is below water level. Wind tides produced by south winds and northers probably increase discharge several times a year to affect channels on the delta and hurricane tides of 3 feet are relatively frequent since they would occur with most hurricanes that strike the Texas coast. The difference in frequency of events that produce these features also reflects their age. The St. Joseph fan apparently began to form on an inlet flood delta platform about 1700 years ago (Andrews, 1967, 1970), while the flood delta at Brown Cedar Cut is only about 40 years old.

There are many "ifs" in these calculations but the velocities and discharges are not unreasonable. It is significant the discharges at Brown Cedar Cut and Vinson Slough, estimated from channel lengths, would be compatible with discharges computed from entrance cross-section, if velocities at spring tide conditions were assumed. The velocities through the entrance cross-section during the actual event, no doubt would depend on the rate of rise in the tide, but probably would fall within the range of velocities observed at inlets on sandy coasts. This is because the ability of currents to erode channels is a function of grain size and the critical velocity necessary to erode and transport that grain size.

Appendix E.

Table of general physiographic characteristics and processes.

MSL = mean sea level (approximate); MHW = mean high water (approximate); Sand = fine quartz sand; Shell(y) = fragments and whole shells, usually unsorted sizes; Mud = silty clay.

Feature	Process	Characteristic Vegetation	Sediment	Description
SURGE CHANNEL	storm surge (mostly flood currents at high tides)	none	depressions are scoured into sand or muddy sand	elongate, waterfilled depressions oriented perpendicular to inlet shoreline
STORM-TIDAL FLAT	storm surge (may be inundated during wind-tides and spring tides)	filimentous algae mats where most frequently inundated; otherwise usually barren of vegetation; locally the oyster grass, Spartina alterniflora, colonizes depressions on low flats	sand or muddy sand	low flats spreading out from surge channels towards Espiritu Santo Bay; range from just below MSL to just above MSL; relief slight (about 1 foot) and in the form of bars and depressions
MOUND	mostly storm surge (tides 5 feet or more above MSL)	distinct plant zonation from sparse grasses and succulents (about 1-4 feet above MSL) (con't.)	sand to v. shelly sand; shell largely concentrated on surface of some mounds	most elongate parallel to surge channels and storm tidal flats; some mounds form as storm aprons behind storm beaches; (Con't.)

Feature	Process	Characteristic Vegetation	Sediment	Description
MOUND (Con't.)		to dense grasses (greater than 4 feet); mesquite and salt cedar on highest, best drained mounds		some scattered unvegetated low mounds located behind higher vegetated mounds and at distal ends of surge channels; usually overlie muddy sand of marsh or storm-tidal flat
STORM-APRON	combination of storm surge and wave action with tides greater than 3 feet above MHW	mostly unvegetated (may have mound plant zonation where inactive)	shelly sand	usually composed of overlapping lobes extending from shell beach: surface relatively flat with steep avalanche slope at distal margin
STORM BEACHES	steep, destructive waves accompanying tides greater than MHW	none	sand, shelly sand or shell	steep erosional beach-face and storm aprons; intertidal zone usually cut into muddy sand underlying mounds or armored with shells eroded out of the beachface, and is sometimes barren of loose sandsized material; shell beaches have constructional steps usually above MHW

Feature	Process	Characteristic Vegetation	Sediment	Description
INLET-MARGIN SHOAL				
a. In front of storm beach	storm waves and inlet currents)	none	sand, some shell	subtidal; gently sloping from shoreline to about 3 foot depth contour slope then steepens into axial trough
b. vegetated	storm waves (and inlet currents)	seagrasses during summer: mostly *Diplanthera wrightii* in shallow water, *Thalassia testudinum* on deeper bars at edge of shoal; isolated clumps of oyster grass, *Spartina alterniflora*	none	same; usually not located on shoal adjacent to storm beaches
INLET-MARGIN GULF BEACH	full spectrum of waves (some currents)	none	sand	usually built in front of erosional storm beach at mound fronts; constructional intertidal beach mapped as inlet-margin shoal; storm berm mapped as storm beach; dominant drift to north

Feature	Process	Characteristic Vegetation	Sediment	Description
SALT MARSH	plant baffling of fines; colonization of sub-tidal flats by salt marsh plants between storms	oyster grass, *Spartina alterniflora*; succulents, *Batis Maritima* and *Salicornia perennis*; the black mangrove, *Avicennia nitida*, lines tidal channels and marsh islands in Espiritu Santo Bay	mud and sandy mud	usually found in intertidal areas sheltered from storm waves and currents; composed of subtidal ponds, tidal creeks that drain marsh and low relief bars and levees; oyster clumps abundant in deeper creeks and among thick stands of *Spartina alterniflora*
TIDAL CHANNELS	currents	none	?	slightly sinuous channels that flow across marsh to connect two large inland bodies of water with lesser tidal ranges than the Gulf of Mexico (dredged channels are usually straight)
LAGOON SHOALS a. unvegetated subtidal flat	? (probably currents)	none	muddy sand	flat or gently sloping surface of firm sediment (relative to deeper grassflats), in water usually less than 1.5 feet deep usually located in areas sheltered from most storm

Feature	Process	Characteristic Vegetation	Sediment	Description
LAGOON SHOALS (Con't.)				(Con't.) waves and currents; opposite large tidal channels, and in re-entrants adjacent to storm tidal flats with well-defined surge channels
b. lagoon grassflat (undivided)	? (probably currents)	mostly *Diplanthera wrightii*	muddy sand to mud, with whole shells and fish-macerated shell fragments	similar location as subtidal flat, except occurs in water between 1-3 feet deep

Appendix F.

Correlation of physiographic terms used for the Flood Delta at Pass Cavallo.

This paper	Hoover, 1968	Andrews, 1966
INLET-MARGIN SHOAL		
a. unvegetated	inlet margin shoal	none
b. with *Spartina alterniflora*	salt marsh	none
c. grass flat (undivided)	inlet margin shoal (*Thalassia* grassflat) north of profile IV *Diplanthera* - *Ruppia* grassflat south of profile IV	none
STORM BEACHES AND STORM APRONS (undivided)		
a. sand (opposite sand mound)	none	none
b. shell (and storm aprons)	shell beach and storm apron	storm ridge
STORM-TIDAL FLAT		
a. barren and surge runway	unvegetated subtidal flat and supratidal flat	mudflat, marsh outer fan margin
b. with vegetated depressions	unvegetated subtidal flat and salt marsh	outer fan margin mudflat, marsh
c. with salt marsh and ponds	unvegetated subtidal flat and salt marsh	outer fan margin mudflat, marsh

Appendix F. (Con't.)

Correlation of physiographic terms used for the Flood Delta at Pass Cavallo.

This paper	Hoover, 1968	Andrews, 1966
SURGE CHANNELS	some subtidal flats, and *Diplanthera* grassflat	"washover and distribution channels"
MOUNDS (sand and shell)	vegetated mounds	(vegetated) eolian mounds
a. high mound (vegetated)	vegetated mounds [shell]	[sand and mud]
b. low mound, mostly sand (barren to sparsely vegetated)	none	distributary channel and mound
LAGOON SHOAL		
a. lagoon grassflat (undivided)	(*Thalassia* - on deeper bars behind Grass Island?)	none
b. unvegetated subtidal flat	unvegetated subtidal flat	none
SALT MARSH		
a. *Spartina alterniflora* marsh	salt marsh (undivided) and tidal channels and creeks	marshes, marsh creeks and ponds
b. salt marsh undivided (dominantly *Batis* and *Salicornia* marsh)	salt marsh (undivided) tidal channels and creeks	marshes, marsh creeks and ponds
TIDAL CHANNELS		
a. Saluria Baylou and Big Bayou	Corpus Christi Bayou	none
b. new tidal channels in Bayucos Is.	tidal channels and creeks	none

Appendix F. (Con't.)

This paper	Hoover, 1968	Andrews, 1966
OYSTER REEFS	Oyster banks	none
MADE LAND	spoil	none
BARRIER ISLAND DUNE RIDGES	none	Dune Ridges
COPPICE DUNES	none	none

Appendix G.

List of maps, charts and aerial photographs.

USCGS Work Sheets

Year	Months	Scale	Title
1873	Jan. - April	1:20,000	Espiritu Santo Bay hydrography
1856	?	1:20,000	Pass Cavallo hydrography
1874	May - July	1:10,000	Outer bar at Pass Cavallo
1934	Nov. 1934 - June 1935	1:10,000	Outer bar at Pass Cavallo

U.S. Coast and Geodetic Survey Navigation Charts

No.	Edition	Scale	Title and Remarks
208	1918	1:80,000	Lavaca and San Antonio Bays-Pass Cavallo surveyed 1887
520	1867 1905	1:40,000	Galveston Entrance
1117	1963	1:460,732	Galveston to Rio Grande
1283	1939	1:80,000	San Luis Pass to Matagorda Bay-Brown Cedar Cut surveyed 1934 or 1935
1284	1939 1965 1970	1:80,000	Matagorda Bay and approaches-Pass Cavallo surveyed 1934 and the axial trough area was omitted at Pass Cavallo in 1965 and 1970
889	1965	1:40,000	Cedar Lakes to Espiritu Santo Bay
889-SC	1970 1971 1972		Cedar Lakes to Espiritu Santo Bay-shorelines and storm shoaling reported in Pass Cavallo but axial trough omitted after 1965

Appendix G. (Continued)

USGS 7 1/2 Minute Quadrangle Topographic Maps

No.	Edition	Scale	Title and Remarks
	1952	1:24,000	Port O'Connor, Pass Cavallo SW, Decros Point, St. Charles Bay SE, St. Charles Bay SW- culture and drainage from 1947 aerial photos; topography from 1952 plane table surveys; hydrography from USCGS charts (probably 1947 ed.)

Aerial Photography

Date	Source	Description
1952-1953	USDA Photo Index Sheets 1" = 1 mi.	Matagorda and Calhoun Counties
1934	Tobin controlled aerial mosaics approximate scale: 1" = 2000'	Same area as 7 1/2 minute topographical sheet
1958	Tobin controlled aerial mosaics approximate scale: 1" = 2000'	Same area as 7 1/2 minute topographical sheet
1971	NASA high altitude aerial photographs	Color and color infrared film

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